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EXPERIMENTAL EVALUATION OF SELF-TUNING CONTROL OF A BINARY DISTILLATION COLUMN

by

© Henry Y. Lieuson

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
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FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled EXPERIMENTAL EVALUATION OF SELF-TUNING CONTROL OF A BINARY DISTILLATION COLUMN submitted by Henry Y. Lieuson, B.ApSc., in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE in PROCESS CONTROL.

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ABSTRACT

This work concerns the experimental evaluation of the self-tuning controller (STC) on a pilot scale distillation column. The evaluation of the STC is done by comparing the performance of the STC with that of well tune proportional-integral-derivative (PID) controllers.

The ST and PID controllers are used to control the terminal compositions of the column when it is subjected to step changes in the feed flow rate. The controllers are tested in the following configurations: top composition control, bottom composition control, and simultaneous compositions control. For the self-tuning controller, dual ends control is performed using both the multiloop and multivariable arrangements. The performance of the controllers is quantified by considering the sum of the absolute error values over a specified time period after the feed flow rate is changed.

The experimental results show that for all the different configurations tested, the self-tuning controller is equal to or better than the PID compensator. The STC is found to be very robust in that it can handle deterministic disturbances (feed flow changes) as good as a well tuned PID compensator even though feedforward control action is not added. With the addition of feedfoward compensation, the STC performance is superior to that of the PID controller.

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1. INTRODUCTION

1.1 INTRODUCTION

Interest in improving terminal composition control strategies for distillation columns has increased in view of the dramatic increases in energy cost. With better control, less over purification is needed to guarantee product specification. The result is reduced expenditure in both heating and cooling medias hence lowering energy requirements.

Over the years, considerable effort has been made to find better control methods that would imporve the control performance over that of the conventional feedback proportional-integral- derivative (PID) controller [1]. Some of the approaches have been implemented on the pilot plant distillation column at the University of Alberta with varying degree of success [2-9]. The difficulties experienced with many of the strategies that have been tested stem from the fact that the techniques were designed to handle linear systems. Unfortunately, the distillation column is clearly a nonlinear system [9]. When a controller is tuned to perform well for one disturbance, the control behavior for another disturbance, or set point change may not be satisfactory. To compensate for nonlinearity, the controllers have to be retuned. An ideal controller would be an adaptive controller where the parameters of the controller change to compensate for changes in process condition. The self-tuning regulator (STR) is such a controller [10]. In the self-tunning regulator, a recursive identification scheme is used to identify either the parameters of a stochastic model for the process or the controller parameters directly. In either case, the control parameters will be changed to suit changes in operating condition.

The self-tuning regulator has been developed from work done by Åström and Wittenmark [10-11], Peterka [12] and Clarke et al. [13-18]. As originally proposed, the controller was for a single input-single output (SISO) system. Borisson [19], Keviscky et al. [20-21] and Morris et al. [22-24] extended the work to handle a class of multivariable cases.

1.2 OBJECTIVE

The object of this study is to experimenatally evaluate the performance of the self-tuning controller (STC) as modified by Morris et al. [24] on the pilot plant distillation column at the University of Alberta. The STC will be studied in single loop, multiloop and multivariable configuration. Results for the self-tuning controller will be compared to those for well tuned proportional-integral-derivative (PID) controllers. Both the STC and PID controller will be used to control the terminal composition of the distillation column when the column is subjected to feed flow disturbances.

1.3 THESIS ORGANIZATION

The thesis will be separated into six chapters. The first chapter gives an introduction. Chapter two contains a survey of the work done to date and a brief discussion of the theory underlying the STC. Extensions to the originally proposed scheme by Åström and Wittenmark [10] will be presented and the actual algorithms used in this study will be derived. Chapter three describes the experimental equipment used in this study. Chapter four deals with the selection of the manipulated variable for control of distillate composition. An analysis of the internal reflux ratio will be given to show which of the manipulated variables, reflux flow or distillate flow should be used. Experimental open loop responses will be presented to show the sensitivity of distillate composition to reflux flow and distillate flow manipulations. Chapter five contains the expermental results. The results will be presented in the following manner:

a. single loop control for overhead composition;
b. single loop control for bottom composition;
c. simultaneous control in multiloop configuration;
d. simulatneous control in multivariable configuration.

Finally, Chapter six summarizes the conclusions and recommendations borne out by this study.

2. DEVELOPEMENT OF THE SELF-TUNING CONTROLLER

2.1 INTRODUCTION

The self-tuning regulator as proposed by Åström [10] as the name implies is an adaptive controller. The algorithm consists of two stages at every sample interval. The first stage is a recursive least square identification scheme to obtain the parameters of a linear stochastic model used to describe the process being controlled while in the second stage a control signal is calculated using minimum variance of the output as a criterion. The parameters estimated from the identification step are used directly as if they are the true parameters. Åström [10] has shown that for systems with constant parameters, if the parameters converge, the controller will converge to the true minimum variance controller. The structure of the self-tuning regulator is shown in Figure 2.1.

There are many advantages in using a self-tuning regulator. First, it is an adaptive controller. Since the parameters of the model are being constantly updated, changes in the process parameters are automatically accounted for. For a nonlinear plant, the parameters identified will give a linearized approximate model of the nonlinear plant. As the operating conditions change, the parameters readjust to linearize the model around the new operating point. For a plant with time varying properties, again the parameters will adapt to the new condition.

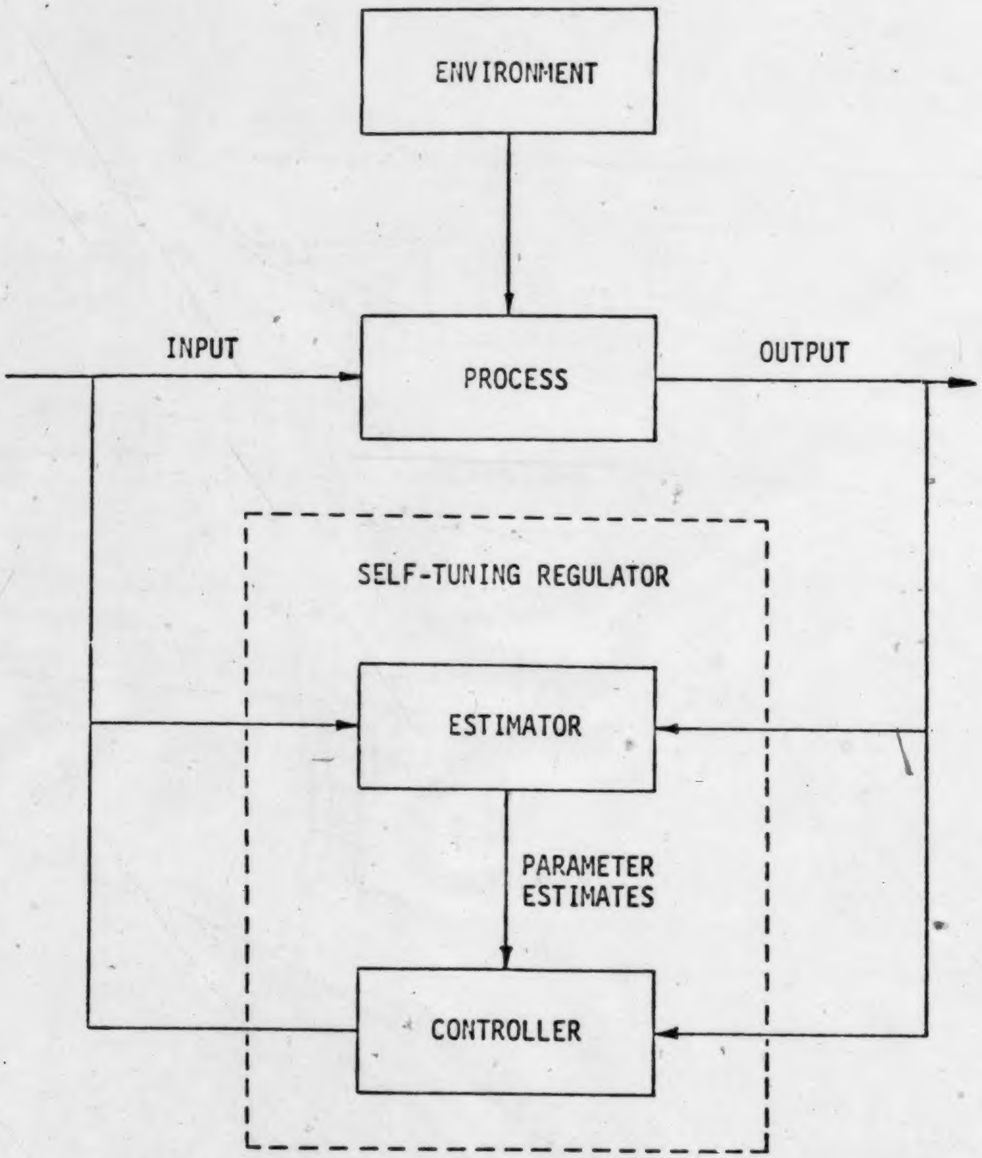
ENVIRONMENT
INPUT
PROCESS
OUTPUT
SELF-TUNING REGULATOR
ESTIMATOR
PARAMETER ESTIMATES
CONTROLLER

Figure 2.1 Basic Structure of the Self-Tuning Regulator

Second, as it is self-tuning, limited knowledge of the system to be controlled is needed. There is no need to do a lengthy background identification test to obtain model parameters. Although certain parmeters have to be specified, these parameters are readily obtained in comparison to determining the constants for a well tuned PID controller. Three, since a model is being used to do the control calculation, there is an inherent predictor. For a system with time delay, the predictor removes the effect of time delay on the system characteristic equation. The process is controlled as if there was no time delay. Finally, by using a stochastic model formulation, random disturbances such as measurement or process noise are automatically accommodated.

2.2 LITERATURE SURVEY

2.2.1 Historical Development of Self-Tuning Regulator

The idea of combining estimation and control in one algorithm is not new. Kalman [25] in 1958 formulated a simplified algorithm that attempted to do both estimation and control at the same time. However, the theory was insufficient and digital computers were not available for process control.

Åström was first involved with the self-tuning regulator when he and Bohlin presented a general form for stochastic models [26]. They considered the maximum likelihood technique for identifying the parameters of linear stochastic models structured according to their general form. Subsequently, Åström [27] looked at the accuracy of the estimates obtained and the possibility of using recursive least squares to identify the parameters.

Peterka [12] then used the Åström-Bohlin model formulation to derive an algorithm that combined estimation of the model parameters and calculation of the control law. He used recursive least squares to identify the parameters of the Åström-Bohlin model; with the model estimates available, a minimum variance of the output was used as the criterion for determining controller action. For some conditions, Peterka found that the controller used was identical to the minimum variance controller that could be derived had the model parameters been known.

Following Peterka's work, Åström and Wittenmark [28] did a thorough study looking at seperate and combined estimation and control stratergies. They considered models that have constant unknown parameters and models that are time-varying Gauss-Markov processes. With Peterka's results and their own work, Åström and Wittenmark formulated the self-tuning regulator [10]. They proved two theorems concerning the self-tuning regulator. Using weak assumptions, they showed that if the parameters converged, then the covariance of the output variable and the crosscovariance between the output and input variable would tend to zero. Futhermore, it was shown for systems with constant parameters that if the parameters converged, the controller would converge to the minimum variance controller that could be derived if the model parameters were known. Results of a detailed simulation study using the self-tuning regulator were presented by Wittenmark [29].

A more complete survey of the different studies that led to the formulation of the self-tuning regulator has been given by Chang [30]. The papers by Clarke [18] and Åström [11] are excellent reviews of many of the self-tuning studies that have been performed.

2.2.2 Modification and Extension

In its original formulation, the self-tuning regulator had very few options. For instance, there was no set point following capability. Many extensions and modifications have since been added to increase the generality and robustness of the controller.

Wittenmark has extended the regulator by adding features to allow set point following for the output variable and feedforward action for measurable disturbances [29].

Clarke et al. [13-18] have presented a generalized version of the self-tuning regulator. The term self-tuning controller designation is used for the Clarke approach to distinguish this type of controller from the self-tuning regulator for the Åström approach. In Clarke's scheme, instead of identifying the parameters of a model and then subjecting the identified model to some control criterion, the controller parameters are identified directly. In addition, the cost function for the controller is modified to include control effort, process output and set point following. Inclusion of control effort into the performance criteria achieves two objectives. Adding a penalty for control effort causes the control output to remain within the constraint limits. The 'bang-bang' controller response that is observed with minimum variance controller is prevented. Second, it can be shown that with the appropriate choice of control weighting, systems that are nonminimum phase can be made closed-loop stable [14]. In a treatment of nonminimum phase systems, Cegrell and Hedqvist [31] have proposed a similar solution to that used by Clarke. Åström [32], Åström and Wittenmark [33], Turtle and Phillipson [34] and Peterka [12] have suggested the use of suboptimal stratergies to handle such systems.

Morris [22-24] inturn has generalized the work presented by Clarke. He has introduced a discrete compensator in PID form for the control weighting used in the cost function. The PID controller is suggested because no offset results when a set point change is made and futhermore, the characteristics of the PID algorithm are well understood. Set point model following is added to allow the process output to change according to any user specified response when a set point change is made; e.g., the output can be made to follow a first order response with some specified time constant. By allowing the output to change slowly, there is no need for excessive control action at the start of a set point change.

Morris has further extended the controller to handle multivariable systems with an equal number of inputs and outputs. The multivariable system is reduced to a series of decoupled single loop controllers. The decoupling is achieved by using the feedforward option to handle the interaction between the individual loops; i.e., the interactions between the loops are treated as measurable disturbances. This approach removes the need to identify directly the parameters (matrices) of a multivariable system. Direct identification of such system has been considered by Gustavsson et al. [35].

Åström and Peterka have considered extending the self-tuning regulator to the multivariable case for systems with constant and unknown parameters [36]. They looked at identifying the parameters of the multivariable model directly. Borrison [19] and Keviczky [20] have presented algorithms to handle multivariable systems that identify the parameters of the multivariable structure directly. De Keyser [37] has proposed a multivariable self-tuning scheme that calculates a control output based on the identified estimates and the covariance of the estimates. With this approach, excessive control is prevented when the parameters are bad; in effect, a more cautious controller is devised.

Different identification schemes have been considered for the self-tuning regulator. Aside from normal least squares, other methods that have been tried include: stochastic approximation [38], extended least squares [39] and maximum likelihood [40]. Recently, it has been shown that the standard least square identification method can lead to problems when a system experiences no disturbances over a long period of time [24]. Without any disturbance, the identification scheme receives no new information and as a result, the covariance matrix tends to 'blow-up' or lose positive definiteness. In either case, the parameters will diverge causing stability problems with the controller. To overcome this problem, Morris [24] has proposed modifying the normal least square scheme by simply updating the square root of the covariance matrix. Morris also proposed to employ a recursive learning estimator [24] once reasonable estimates have been obtained with normal least squares. Clarke [18] has reported alternate solutions which modify the identification after a 'no disturbance' situation is detected. One possibility would be to stop the identification if the determinant of the covariance matrix exceeds some specified limit or to introduce a disturbance if this condition occurs. The third approach Clarke suggested was that the forgetting factor be adjusted so that it tends to unity if no disturbance is entering the system.

2.2.3 Application

Numerous applications of the self-tuning regulator for the control of various different types of systems have been reported. Those considered pertinent to this work will be briefly discussed. Wittenmark and Borisson [40] have used the self-tuning regulator for controlling the moisture content of a paper machine. They found that the regulator was able to handle nonstationary disturbances and that the choice for the number of parameters in the model was unimportant. Cegrell and Hedqvist, on a different paper machine, used a self-tuning regulator with five inputs and one output [41]. They reported that the self-tuning regulator, in comparison to a PI regulator, reduced the output variance during quality change and mill step-up. In addition, their experience was consistent with that of Borisson and Wittenmark in that they also concluded that the number of parameters in the model was unimportant.

Borisson and Syding have reported the use of a self-tuning regulator on an ore-crusher [42]. They found that the regulator was able to adapt to changes in the characteristics of the ore feed and the crusher itself. As a direct result of using the self-tuner, a 10% increased in production was achieved over that possible using PI control.

Dumont and Belanger [43-44] have used the self-tuning regulator for controlling a titanium oxide kiln. They were able to reduce the number of parameters required in the self-tuning regulator by applying the regulator on a plant that was already controlled by a fixed parameter regulator. They reported that with this type of stratergy, instead of a normal 10-12 hours of offspecification product during a grade change, the switchover time was reduced to 2 hours.

Keviczky et al. [21] and Westerlund et al, [45] have applied the self-tuning regulator to control of cement raw material mixing. The application by Keviczky was on a multivariable system and the control criteria was based on minimum variance of the output and some required average over a time duration. In both applications, it was found that the STR gave results that were superior to those achieved with a conventional control approach.

Various authors have presented results from applications of the self-tuning regulator to pilot scale equipment. Sastry et al. [46] reported on the performance of the self-tuning regulator for controlling the overhead composition of a binary distillation column. In general, the self-tuning regulator performed better than a PI controller. Chang [30] used the self-tuner on a pilot scale evaporator. He considered how the various design parameters affected the performance of the regulator. Harris et al. [47] studied the control of a pilot scale packed bed reactor with the self-tuning controller. The reaction involved was extremely temperature sensitive which resulted in highly nonlinear and nonminimum phase system behaviour. The self-tuning controller was reported to be superior to the conventional PI algorithm. The study also looked at the problem of 'parameter-windup'; this is a situation when the parameters starts to diverge because the controller output is clamped at one of the constraints.

Applications of the self-tuning regulator have also been reported for the control of an enthalpy exchanger[48], digester[49], absorption column[50] and ship steering[51].

2.2.4 Convergence and Stability Analysis

Ljung has presented results for convergence analysis of general recursive stochastic algorithms [52-56]. His approach was to associate the algorithms with an ordinary differential equation so that the convergence properties of the algorithm could be obtained by looking at the stability properties of the differential equation. Åström has used Ljung's results to analyze the self-tuning regulator [11].

For the self-tuning controller, convergence analysis is based on the idea of treating the controller as a feedback system [57,58]. Using the Martingale theorem [59,60], Gawthrop [61] has shown that under certain conditions, convergence will occur with a probability of 1.0.

2.3 DERIVATION OF THE SELF-TUNING CONTROLLER

2.3.1 Control Law Formulation

A single input-single output (SISO) stochastic process can be described by:

$$Ay_t = z^{-k}Bu_t + C\xi_t + z^{-k^L}Lv_t \tag{2.1}$$

where A,B,C,L are polynomials in z^{-1} with $a_0 = 1$, $b_0 = 0$ and $c_0 = 1$ with $z^{-N}y_t$ denoting the value of y, N samples in the past. The terms y_t, u_t, ξ_t, v_t are respectively the process output, control input, random disturbance and measurable disturbance. The system is considered to be of order n with a time delay equal to k times the sample time and k^L the time delay associated with the known disturbance. It is also assumed that C has roots that are within the Z-domain unit circle and that ξ_t is a random uncorrelated noise signal with zero mean. The controller is designed to minimize the cost function:

$$J_1 = E\{(Py_{t+k} - Rw_t)^2 + (Q'u_t)^2\} \qquad (2.2)$$

where P,R,Q' are polynomials in z^{-1} which allow weighting to be applied to the output, set point and control effort. The term $(Py_{t+k} - Rw_t)$ provides set point following while $(Q'u_t)$ puts a penalty on control action. From the form of the cost funtional it can be seen that if $Q'u_t$ does not tend to zero at steady state, $Py_{t+k} - Rw_t$ will tend to some constant other than zero and the process output will exhibit an offset (cf. equation (2.23)).

In order to minimize J_1, an expression is required for y_{t+k} in terms of past input and output data. Here, y_{t+k} denotes the k-step ahead predictor for the output. The basic derivation of the self-tuning regulator was given first by Åström [10]. However, the ensuing derivation follows closely the formulation given by Clarke [13] and Morris and coworkers [24].

Expressing Equation (2.1) in terms of the k-step ahead predictor gives:

$$y_{t+k} = \frac{B}{A} u_t + z^k \frac{C}{A} \xi_t + z^{k-k^L} \frac{L}{A} v_t \qquad (2.3)$$

In Equation (2.3), at time t, providing k^L is larger than k, only the future random disturbances from time t+1 to t+k are unknown. Separating $z^k(C/A)\xi_t$ into disturbances up to the present time and those at future time gives:

$$z^{k}\frac{C}{A}\xi_t = E'z^{k}\xi_t + \frac{F'}{A}\xi_t \tag{2.4}$$

where $E'z^k\xi_t$ represents the future disturbances and $(F'/A)\xi_t$ equals the disturbances up to the present time. The polynomials E' and F' have terms:

$$E' = 1 + e'_1 z + \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot + e'_{k-1}z^{-(k-1)} \tag{2.5}$$

$$F' = f'_0 + f'_1 z + \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot + f'_{n-1}z^{-(n-1)} \tag{2.6}$$

Substitution of Equation (2.4) into the predictor equation (2.3) and noting that $z^k\xi_t$ is the same as gives:

$$y_{t+k} = \frac{B}{A}u_t + E'\xi_{t+k} + \frac{F'}{A}\xi_t + z^{k-k^L}\frac{L}{A}v_t \tag{2.7}$$

The random disturbance ξ_t up to time t can be expressed in terms of previous inputs and outputs by rewriting Equation (2.1) in terms of ξ_t as:

$$\xi_t = \frac{A}{C}y_t - z^{-k}\frac{B}{C}u_t - z^{-k^L}\frac{L}{C}v_t \tag{2.8}$$

Using Equation (2.8) to substitue for ξ_t in Equation (2.7), after some rearrangement yields:

$$y_{t+k} = E'\xi_{t+k} + \left[\frac{1}{A} - \frac{z^{-k}F'}{AC}\right]Bu_t + \frac{F'}{C}y_t + \left[\frac{1}{A} - \frac{z^{-k}F'}{AC}\right]z^{k-k^L}Lv_t \tag{2.9}$$

From Equation (2.4), it follows that the terms in the brackets simplify to E'/C so Equation (2.9) becomes:

$$y_{t+k} = E'\xi_{t+k} + \frac{E'B}{C}u_t + \frac{F'}{C}y_t + \frac{E'L}{C}z^{k-k^L}v_t \tag{2.10}$$

Since ξ_t has been assumed to be a white noize sequence, the future disturbance is expected to be zero. Taking the expectation of Equation (2.10), the predicted output is given as:

$$y^*_{t+k} = \frac{E'B}{C}u_t + \frac{F'}{C}y_t + \frac{E'L}{C}z^{k-k^L}v_t \tag{2.11}$$

where the asterisk denotes a predicted quantity.

All the terms on the right hand side of Equation (2.11) are known at time t provided k^L is equal to or greater than k; i.e., the time delay in the feedforward path must be larger than the time delay for the control action. If the above condition is not true, a predictor for future measured disturbances is needed. However, for most actual processes, the time delay for the measured disturbance is much larger than the time delay for the control variable.

The performance criteria given by Equation (2.2) requires a weighted output. Applying 'P' weight to Equation (2.3) yields:

$$Py_{t+k} = \frac{PB}{A} u_t + \frac{PC}{A} \xi_{t+k} + z^{k-k^L} \frac{PL}{A} v_t \qquad (2.12)$$

Now by defining:

$$P = P_N \;/\; P_D \qquad (2.13)$$

and,

$$\frac{PC}{A} = E + \frac{z^{-k} F}{AP_d} \qquad (2.14)$$

Using Equations (2.12) to (2.14) and following the derivation used for the k-step predictor (Equation (2.10)), the weighted output Py_{t+k} can be written as:

$$Py_{t+k} = E\xi_{t+k} + \frac{F}{CP} y_t + \frac{EB}{C} u_t + \frac{EL}{C} z^{k-k^L} v_t \qquad (2.15)$$

As before, the best estimate of future disturbances is zero so the k-step ahead weighted output predictor is given by:

$$(Py_{t+k})^* = \frac{F}{CP} y_t + \frac{EB}{C} u_t + \frac{EL}{C} z^{k-k^L} v_t \qquad (2.16)$$

The actual weighted output and the predicted output are related by:

$$Py_{t+k} = (Py_{t+k})^* + \varepsilon_{t+k} \qquad (2.17)$$

where, $\varepsilon_{t+k} = E\xi_{t+k}$. Substituting the weighted output given by Equation (2.17) into the cost function yields:

$$J_1 = E\{\, [(Py_{t+k})^* + \varepsilon_{t+k} - Rw_t]^2 + [Q'\,\text{[illegible]}_t]^2 \,\} \qquad (2.18)$$

Since it has been assumed that the random disturbances are uncorrelated with either the input or output, the expectation simplifies to:

$$J_1 = E\{ [(Py_{t+k})^* - Rw_t]^2 \} + E\{[Q'u_t]^2\} + \sigma^2_{t+k} \quad (2.19)$$

where $\sigma^2{}_{t+k}$ is the variance of the random disturbances.

The cost function is minimized by setting the partial derivative $\partial J_1/\partial u_t$ to zero. To obtain the true optimal solution, the expectation operator must be included in the differentiation [62]. However, a complicated control law results so instead, a stage by stage optimal controller is used. In this work, following the approach of Clarke and Gawthrop [14], the expectation is removed from Equation (2.19) and the resulting equation is differentiated with respect to u_t. The controller that results is optimal each time the control calculation is performed. Although the solution is not globally optimal, Harris [47] has shown that the control response of the suboptimal stratergy is close to the result that is obtained when the true optimal controller is used. Removing the expectation operator, the partial derivative becomes:

$$\frac{\partial J_1}{\partial u_t} = 2[(Py_{t+k})^* - Rw_t] * \frac{\partial (Py_{t+k})^*}{\partial u_t} + 2Q'u_t * \frac{\partial (Q'u_t)}{\partial u_t} \quad (2.20)$$

Performing the necessary differentiation and noting that $(Py_{t+k})^*$ is related to u_t(cf. Equation (2.16)), setting Equation (2.20) to zero gives:

$$[\,(Py_{t+k})^* - Rw_t\,] * \frac{e_0 b_0}{c_0} + q_0{}'Q'u_t = 0 \qquad (2.21)$$

where e_0, b_0, c_0 and $q_0{}'$ are the leading coefficients for the polynomials E, B, C and Q'. Defining:

$$Q = \left[\frac{q_0{}'}{b_0}\right] * Q' \qquad (2.22)$$

and recalling that e_0 and c_0 are equal to 1, Equation (2.21) can be written as:

$$u_t = \frac{1}{Q}\,[\;Rw_t - (Py_{t+k})^*\;] \qquad (2.23)$$

Examination of Equation (2.23) shows that it is similar to a standard feedback control law with the main difference that the feedback value is a predicted output instead of the actual measurement. It follows that the inverse of the control effort weighting is the discrete compensator used in the feedback loop. While any discrete compensator can be used, the PI compensator is selected because its characteristics are widely known. The PI compensator used is of the form:

$$G = \frac{1}{Q} = \frac{k_p(1-z^{-1}) + k_i}{(1 - z^{-1})} \qquad (2.24)$$

The PI compensator is used instead of a PID compensator because derivative action is generally not required for systems without time delay. As the self-tuning controller predicts the output, the effect of process time delay is removed hence derivative action is not necessary. The incremental PI form is used to insure that Qu_t tends to zero at steady state since this is the requirement for zero offset. If Qu_t does not tend to zero at steady state, the difference between the weighted setpoint and the predicted output $(Rw_t - (Py_{t+k})^*)$ is different from zero (cf. Equation (2.23)) At steady state, the expected predicted output is equal to the actual output. If Qu_t does not equal zero, the difference between the weighted set point and output is different from zero so an offset occurs.

The control law can now be formulated in terms of a predicted scalar output defined as:

$$\emptyset^*_{t+k} = (Py_{t+k})^* - Rw_t + Qu_t \qquad (2.25)$$

The control law formulation thus involves the calculation of u_t by zeroing $\emptyset^*_{t+k}$ at every sample instant. The actual scalar output is given by:

$$\emptyset_{t+k} = Py_{t+k} - Rw_t + Qu_t \qquad (2.26)$$

As ε_{t+k} and Py_{t+k} are uncorrelated, the error in the estimates of $\emptyset_{t+k}$ can be obtained from Equation (2.17) as:

$$\emptyset^*_{t+k} = \emptyset_{t+k} - \varepsilon_{t+k} \qquad (2.27)$$

Substitution of the expression for $(Py_{t+k})^*$ from Equation (2.16) into Equation (2.25) yields:

$$C\emptyset^*_{t+k} = F/P_d\, y_t + EBu_t + CQu_t - CRw_t + ELz^{k-k^L} v_t \qquad (2.28)$$

Defining:

$$\bar{y}_t = y_t / P_d \qquad (2.29)$$

$$\bar{w}_t = Rw_t \qquad (2.30)$$

$$\bar{v}_t = z^{k-k^L} v_t \qquad (2.31)$$

$$H = -C \qquad (2.32)$$

$$D = EL \qquad (2.33)$$

allows the control law to be written as:

$$C\emptyset^*_{t+k} = F\bar{y}_t + EBu_t + CQu_t + H\bar{w}_t + D\bar{v}_t \qquad (2.34)$$

Furthermore, the polynomial associated with the control ouput u_t can be defined to be independent of the control weight function by setting:

$$G = EB \qquad (2.35)$$

which then allows the control law to be expressed as:

$$C\emptyset^*_{t+k} = F\bar{y}_t + Gu_t - HQu_t + H\bar{w}_t + D\bar{v}_t \qquad (2.36)$$

Alternatively, all the polynomials involving u_t can be grouped together in the form of:

$$G = \frac{EB + QC}{Q} \qquad (2.37)$$

So the control law takes the form:

$$C\emptyset^*_{t+k} = F\bar{y}_t + GQu_t + H\bar{w}_t + D\bar{v}_t \qquad (2.38)$$

The block diagram of the control law as expressed in Equations (2.36) and (2.38) are shown in Figures 2.2 and 2.3 respectively.

2.3.2 Closed Loop Response

The closed loop response can be obtained by substituting $(Py_{t+k})^*$ given by Equation (2.17) into the control law Equation (2.23). After rearranging the output, y_t is given by:

$$y_t = \frac{1}{P} \{E\xi_t + z^{-k}Rw_t - z^{-k}Qu_t\} \tag{2.39}$$

Solving Equation (2.1) for $z^{-k}u_t$ and substituting into Equation (2.39) yields the closed loop response:

$$y_t = \frac{1}{P} \left[\frac{(EB + CQ)\xi_t + z^{-k}BRw_t + z^{-k^L}QLv_t}{(B + QA/P)} \right] \tag{2.40}$$

The stability of the system is governed by the characteristic equation:

$$PB + QA = 0 \tag{2.41}$$

It is clear that if B is nonminimum phase; i.e. its roots lie outside the z-domain unit circle, by proper choice of Q, the roots of the characteristic equation will still be inside the unit circle. The closed loop response is then stable. It is to be noted that as in the case of the analytical predictor [63] and Smith predictor [64], the effect of the system time delay (z^{-k}) has been removed from

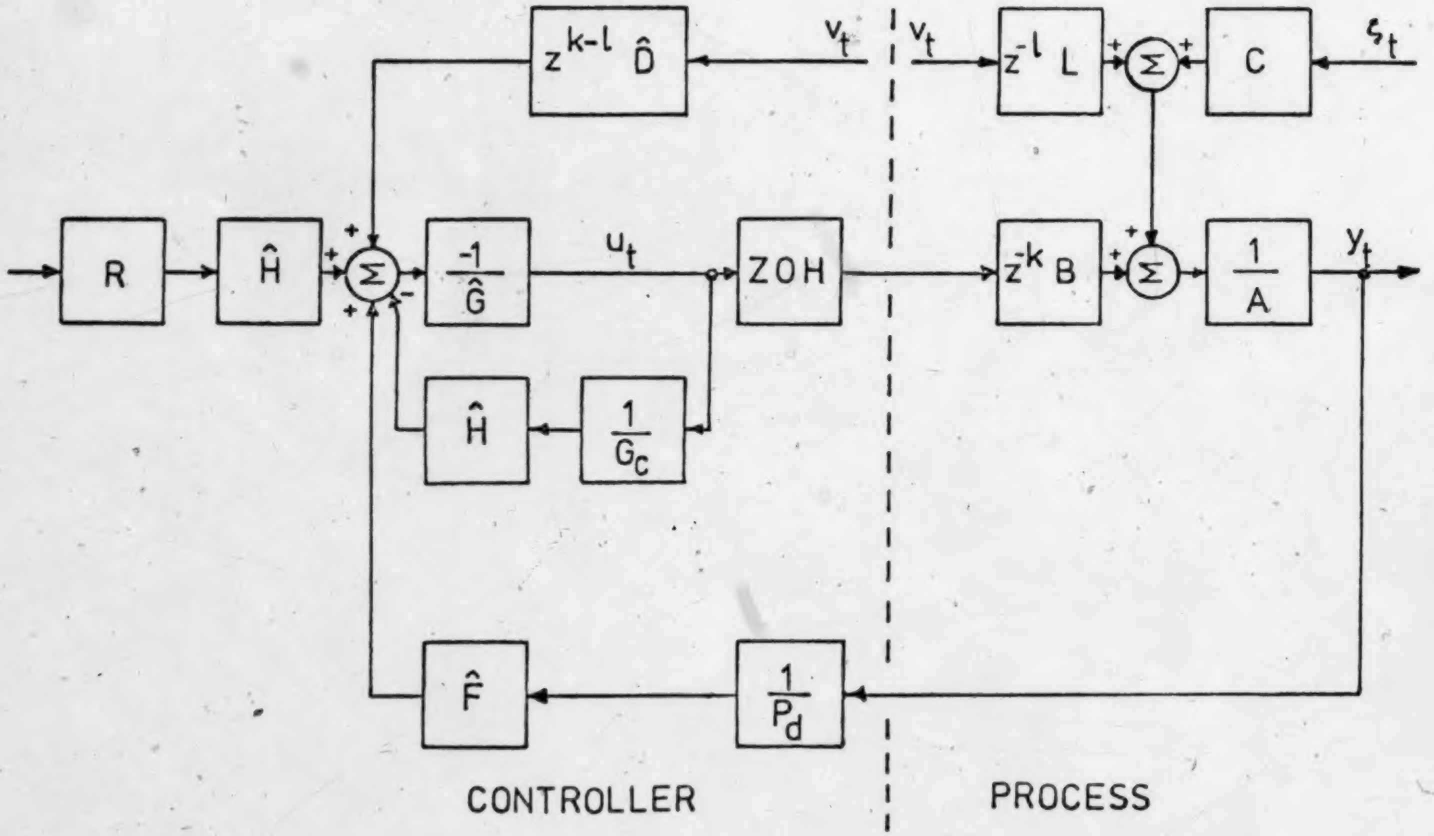
R
$\hat{H}$
Σ
$\frac{-1}{\hat{G}}$
u_t
ZOH
$z^{k-l}\ \hat{D}$
v_t
$\hat{H}$
$\frac{1}{G_c}$
$\hat{F}$
$\frac{1}{P_d}$
v_t
$z^{-l}\ L$
Σ
C
ξ_t
$z^{-k}\ B$
Σ
$\frac{1}{A}$
y_t
+
−
CONTROLLER
PROCESS

Figure 2.2 Block Diagram of Self-Tuning Controller for G=EB

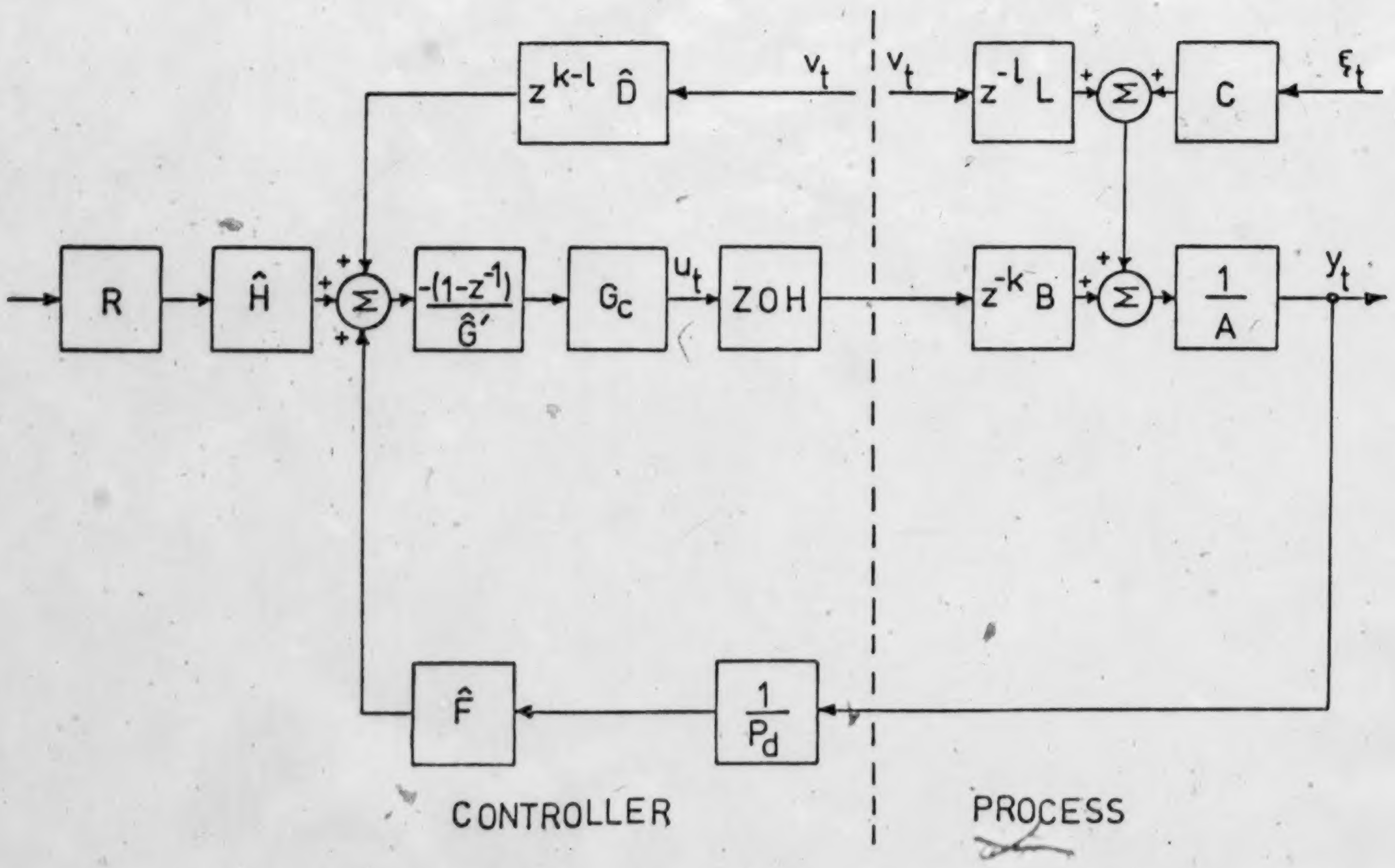
R
$\hat{H}$
Σ
+
+
+
$\frac{-(1-z^{-1})}{\hat{G}'}$
G_c
u_t
ZOH
$z^{k-l}\ \hat{D}$
v_t
v_t
$z^{-l}\ L$
Σ
+
+
C
ξ_t
$z^{-k}\ B$
Σ
+
+
$\frac{1}{A}$
y_t
$\frac{1}{P_d}$
$\hat{F}$
CONTROLLER
PROCESS

Figure 2.3 Block Diagram of Self-Tuning Controller for G=(EB+CQ)/Q

the characteristic equation.

2.3.3 Model Following For Set Point

The ability of the algorithm to force the output to follow a specified response can be clearly seen from Figures 2.2 and 2.3. By changing the weighting functions P and R, the output can be made to follow a desired response. Furthermore, the set point weighting function R can be changed without altering the closed loop stability of the system. In contrast, if the P weight is changed, it will alter the characteristic equation and possibly change the stability of the closed loop system.

2.3.4 Controller Parameter Estimation

The algorithm that has been derived is for a system with known structure and parameters. Yet in practice, this is rarely the case. Even if the order of the model is known, usually the exact process dynamics and hence the model parameters are not known. One possible solution is to use an on-line identification scheme to obtain parameter estimates. The control law can be rendered less sensitive to parameter bias and variation by using a specific structured 'controller-model' [24]. This is true provided the performance function J_1 is minimized when the estimated parameters are used. Subtracting Equation (2.34) from Equation (2.27) and rearranging yields $\emptyset_{t+k}$ in linear regression form, that is:

$$\phi_{t+k} = \underline{X}^{T}{}_{t}\underline{\theta}_{t} + (1-C)\phi^{*}{}_{t+k} + \varepsilon_{t+k} \tag{2.42}$$

where:

$$\underline{\theta}_{t} = [F_{t}, G_{t}, D_{t}, H_{t}]$$

$$\underline{X}_{t} = [\bar{y}_{t}, u_{t}, \bar{v}_{t}, \bar{w}_{t}]$$

The parameters in the $\underline{\theta}_t$ vector can now be estimated using a recursive least squares algorithm [65]. At every sample interval, the parameter estimate vector $\hat{\underline{\theta}}_t$ is updated according to:

$$\phi_{t} = P\bar{y}_{t} - R\bar{w}_{t-k} + Qu_{t-k} \tag{2.43}$$

$$\hat{\underline{\theta}}_{t} = \hat{\underline{\theta}}_{t-1} + \underline{K}_{t}(\phi_{t} - \underline{X}^{T}{}_{t-k}\hat{\underline{\theta}}_{t-1}) \tag{2.44}$$

$$\underline{K}_{t} = \frac{\underline{\underline{P}}^{c}{}_{t}\underline{X}_{t-k}}{(\rho + \underline{X}^{T}{}_{t-k}\underline{\underline{P}}^{c}{}_{t}\underline{X}_{t-k})} \tag{2.45}$$

$$\underline{\underline{P}}^{c}{}_{t+1} = \frac{1}{\rho}\,\underline{\underline{P}}^{c}{}_{t}(1 - \underline{K}^{T}_{t}\underline{X}_{t-k}) \tag{2.46}$$

Here, $\underline{K}_t$ is the Kalman gain vector and $\underline{\underline{P}}^c$ is a symmetric matrix that is proportional to the covariance matrix. To allow tracking of slow time varying parameters, a forgetting factor ρ is used to weight out the effect of past data or alternatively, a positive definite matrix can be added to the $\underline{\underline{P}}^c$ update relationship to weight out old data. In both cases, when the system experiences no disturbance over a long period, the $\underline{\underline{P}}^c$ matrix can become extremely large [24]. This occurs because without any disturbances, no new information can be obtained by the identification algorithm. As a result, the Kalman gains become small and from Equation (2.46), $\underline{\underline{P}}^c(t)$ approaches the value $\underline{\underline{P}}^c(t-1)/\rho$. If the system remains undisturbed over a period of time t, then $\underline{\underline{P}}^c(t)$ is equal to $\underline{\underline{P}}^c(t_0)/\rho^t$, where t_0 refers to the time when the system last experienced a disturbance. As the forgetting factor (ρ) is less than one, as time passes, $1/\rho^t$ becomes very large hence causing the matrix to 'blow-up'. When the $\underline{\underline{P}}^c$ matrix becomes large, limited machine precision may cause the matrix to lose positive definiteness. As a result, the parameters will diverge causing instability in the control loop. The proposed solution, and that adopted in this study, is to modify the identification scheme to update the square root of the $\underline{\underline{P}}^c$ matrix [24]. The square root will always be positive definite and it is inherently of higher numerical precision. Consequently, the control algorithm now consists of using a recursive square root identification to obtain the parameter vector $\hat{\underline{\theta}}_t$ and then using the estimates to calculate a new control output according to the criteria (cf. equation (2.38)):

$$\underline{X}^T{}_t\hat{\underline{\theta}}_t = 0 \tag{2.47}$$

Åström has shown that by using a control law of the form given by Equation (2.47), all vectors with the form $\underline{\theta} = \alpha\underline{\theta}$ will produced the same control [11]. This means that the parameters will not necessarily converge to provide a unique solution. If the parameters converge to an α that is too large or small, numerical problems could result. In addition, as the estimates are being used in the feedback controller, they are correlated with the disturbance. It may then not be possible to identify all the parameters in the $\underline{\theta}$ vector. Åström has proposed that one parameter be fixed to overcome these problems. One obvious choice is to fix the leading coefficient for the set point weighting polynomial providing w_t is not zero. In this case, h_0 should be set to -1 as it is equal to $-c_0$. Alternatively, Astrom has suggested fixing the leading coefficient of the G polynomial; i.e., the scaling parameter for the controller output. He showed that if this parameter is much smaller than the true value, the other parameters will diverge. In contrast, if the parameter is much larger than the true value, the control action becomes very small and convergence of the parameters is very slow.

2.3.5 Extension to Multivariable case

The control structure derived for the SISO case can be extended to a class of multivariable systems by use of the feedforward terms. The system is decoupled by using feedforward action of the manipulated variable of one output as a measurable disturbance for the other outputs. This treatment will be restricted to systems with an equal number of inputs and outputs. In addition, the time delays due to the interactive terms must be greater than the time delay due to the manipulated variable for any given loop.

Consider a multivariable system with M-inputs and M-outputs, the system can be described by the vector-matrix difference equation:

$$z^{-k^{A}_{ij}}[\underline{\underline{A}}][\underline{y}_t] = z^{-k^{B}_{ij}}[\underline{\underline{B}}][\underline{u}_t] + [\underline{\underline{C}}][\underline{\xi}_t] + z^{-k^{L}_{ij}}[\underline{\underline{L}}][\underline{v}_t] \qquad (2.48)$$

where $[\underline{\underline{A}}]$, $[\underline{\underline{B}}]$, $[\underline{\underline{C}}]$, $[\underline{\underline{L}}]$ are polynomial matrices in z^{-1}; $[\underline{y}_t]$, $[\underline{u}_t]$, $[\underline{\xi}_t]$ and $[\underline{v}_t]$ are vectors corresponding to the output, input, noise and feedforward disturbances; k^{A}_{ij}, k^{B}_{ij}, k^{L}_{ij} are the time delays of the output, input and feedforward disturbance for the jth component in the ith loop. The assumption is made that $[\underline{\underline{B}}_0]$ is nonsingular and that the roots of all the row polynomials in $[\underline{\underline{C}}]$ lie inside the z-domain unit circle.

The controller performance index is similar to the SISO case:

$$J = E\{ ([\underline{\underline{P}}][\underline{y}_{t+k}] - [\underline{\underline{R}}][\underline{w}_t])([\underline{\underline{P}}][\underline{y}_{t+k}] - [\underline{\underline{R}}][\underline{w}_t])^T\} + E\{ ([\underline{\underline{Q}}'][\underline{u}_t])([\underline{\underline{Q}}'][\underline{u}_t])^T\} \qquad (2.49)$$

The difference is that $([\underline{\underline{P}}][\underline{y}_{t+k}] - [\underline{\underline{R}}][\underline{w}_t])$ is now a vector instead of a scalar value. As before, $[\underline{\underline{P}}]$, $[\underline{\underline{R}}]$, and $[\underline{\underline{Q}}']$ are matrix weighting functions in z^{-1}. Analogous with the SISO case, $([\underline{\underline{P}}][\underline{y}_{t+k}])$ can be replaced by the predicted vector $([\underline{\underline{P}}][\underline{y}_{t+k}])^*$ yielding the following equation:

$$J = E\{ (([\underline{\underline{P}}][\underline{y}_{t+k}])^* - [\underline{\underline{R}}][\underline{w}_t]) (([\underline{\underline{P}}][\underline{y}_{t+k}])^* - [\underline{\underline{R}}][\underline{w}_t])^T\} + E\{ ([\underline{\underline{Q}}'][\underline{u}_t])([\underline{\underline{Q}}'][\underline{u}_t])^T + [\underline{\xi}_{t+k}][\underline{\xi}_{t+k}]^T \} \qquad (2.50)$$

where $[\underline{\varepsilon}_{t+k}]$ is a vector of weighted prediction errors which is assumed to be uncorrelated with all the inputs and outputs. Minimizing Equation (2.50) by setting $\partial J/\partial[\underline{u}_t]$ to zero gives:

$$\{([\underline{\underline{P}}][\underline{y}_{t+k}])^{*} - [\underline{\underline{R}}][\underline{w}_t]\}[\underline{\underline{B}}_0]^{T} + [\underline{\underline{Q}}'][\underline{\underline{Q}}'_0][\underline{u}_t] = 0 \qquad (2.51)$$

Defining:

$$[\underline{\underline{Q}}] = [\underline{\underline{Q}}'][\underline{\underline{Q}}'_0]([\underline{\underline{B}}_0]^{T})^{-1} \qquad (2.52)$$

the control law can now be written in terms of a predicted vector output as:

$$[\underline{\phi}^{*}_{t+k}] = [\underline{\underline{Q}}][\underline{u}_t] + \{([\underline{\underline{P}}][\underline{y}_{t+k}])^{*} - [\underline{\underline{R}}][\underline{w}_t]\} \qquad (2.53)$$

Replacing $([\underline{\underline{P}}][\underline{y}_{t+k}])^{*}$ with an expression analogous to Equation (2.16) and using similar definition to those in Equations (2.29) to (2.33) and (2.37), the control law becomes:

$$\underset{i\neq j}{z^{k^{A}_{ij}-k^{B}_{ij}}}[\underline{\underline{G}}][\underline{u}_t] = \frac{-1}{[\underline{\underline{Q}}]}\{\underset{i\neq j}{z^{k^{A}_{ij}-k^{B}_{ij}}}\ [\underline{\underline{F}}][\underline{\bar{y}}_t] + [\underline{\underline{H}}][\underline{\bar{w}}_t] + [\underline{\underline{D}}][\underline{\bar{v}}_t]\} \qquad (2.54)$$

By expressing the interactive terms as feedforward disturbances, the parameters can be identified as a series of M loops. Each loop would correspond to the parameters for each row in Equation (2.54). Using recursive least squares identification, the algorithm for obtaining the parameters where i denotes the ith loop, is:

$$\phi_{i_t} = P_i\bar{y}_{i_t} - R_i\bar{w}_{i_{t-k^{B}_{ii}}} + Q_i u_{i_{t-k^{B}_{ii}}} \qquad (2.55)$$

$$\underline{\hat{\theta}}_{i_t} = \underline{\hat{\theta}}_{i_{t-1}} + \underline{K}_{i_t} (\phi_{i_t} - \underline{X}^T_{i_{t-k^B_{ii}}} \underline{\hat{\theta}}_{i_{t-1}}) \qquad (2.56)$$

$$\underline{K}_{i_t} = \frac{\underline{\underline{P}}^c{}_{i_t} X_{i_{t-k^B_{ij}}}}{(\rho_i + \underline{X}^T{}_{i_{t-k^B_{ii}}} \underline{\underline{P}}^c{}_{i_t} \underline{X}_{i_{t-k^B_{ii}}})} \qquad (2.57)$$

$$\underline{\underline{P}}^c{}_{i_{t+1}} = 1/\rho_i * (1 - \underline{K}^T_{i_t} \underline{X}_{i_{t-k^B_{ii}}}) \underline{\underline{P}}^c{}_{i_t} \qquad (2.58)$$

By separating the loops, the identification scheme is simplified. Futhermore, the weighting functions for each loop is treated separately, that is the control effort weighting Q_i can be tuned individually loop by loop. In addition, this implementation allows the used of a different forgetting factor for each loop.

For most processes, the control law given by Equation (2.54) can be simplified since in practice one output in a multivariable system does not directly affect another output. It is the controller action that causes interactions. It follows that $[\underline{\underline{F}}]$ is diagonal and the terms $k^A{}_{ij}$ are zero. The simplified control law is then:

$$[\underline{\underline{G}}][\underline{u}_t] = 1/[\underline{\underline{Q}}] \ \{ [\underline{\underline{F}}][\underline{\bar{y}}_t] + [\underline{\underline{H}}][\underline{\bar{w}}_t] + [\underline{\underline{D}}][\underline{\bar{v}}_t]\} \qquad (2.59)$$

A final note, although the identification is done one loop at a time, in general, the control signals have to be calculated simultaneously. The $[\underline{u}_t]$ vector is obtained directly by solving Equation (2.59). However, for systems with few inputs and outputs, the solution for $[\underline{u}_t]$ can be written out explicity without too much complication so that $[\underline{u}_t]$ can be solved by direct substitution.

3. EXPERIMENTAL IMPLEMENTATION

3.1 DESCRIPTON OF EXPERIMENTAL EQUIPMENT

The pilot plant distillation column in the Department of Chemical Engineering at the University of Alberta is a 22.5 cm diameter column. It has a thermosyphon reboiler, a total condenser and eight bubble cap trays spaced 30.5 cm apart with four bubble caps per tray. A detailed description of the column and the associated equipment is given by Svrcek [2] and Pacey [6].

The feed is a water-methanol mixture containing 50% by weight methanol. The feed enters at a rate of 18.08 g/s and is separated to an overhead composition of 95% by weight methanol and a bottom composition of 5% by weight methanol. The control objective is to minimize variations in terminal compositions when the feed flow rate is changed by 25% from its normal steady state feed flow rate.

The distillation column is extensively instrumented to give maximum flexibility for studying different control stratergies. A schematic diagram showing the extent of the instrumentation is given in Appendix A. All the measurable variables that affect the performance of the pilot plant column are recorded. Temperature measurements are taken for the liquids at every tray, the reboiler and condenser. As well, temperatures and flow rates of the bottoms, distillate, feed, reflux and steam are recorded. The cooling load for the condenser is monitored by measuring the inlet and outlet temperatures and flow rate of the cooling water. The overhead composition is measured continuously using a capacitance probe while the bottom composition is obtained by using a Hewlett-Packard (HP) model 5720A gas chromatograph equipped with an automatic sampling valve. The sampling configuration is the one developed by Bilec [9]. The chromatogram is analyzed on-line by a HP 1000 mini-computer using a cycle time of three minutes. Additional variables that are measured include the column pressure and the liquid levels in both the condenser and reboiler. All the signals from the measured variables can be brought into the central HP-1000 mini-computer located in the Data Acquisition Control and Simulinion (DACS) center at the Department of Chemical Engineering for access by any program executing in the computer. It should be noted that the central computer is not the same one used for analyzing the gas chromatograph. Figure 3.1 shows how the distillation column is interfaced to the different computers in the DACS center.

The column is instrumented with local analog controllers that control all the flow rates, the condenser and reboiler levels, the feed and reflux temperatures and the column pressure. The instrumentation is such that control of the flows and temperatures can be taken over by the central HP 1000 mini-computer at the DACS center. The computer can assume direct digital control (DDC) or operate in the supervisory mode. With DDC, the computer sends the

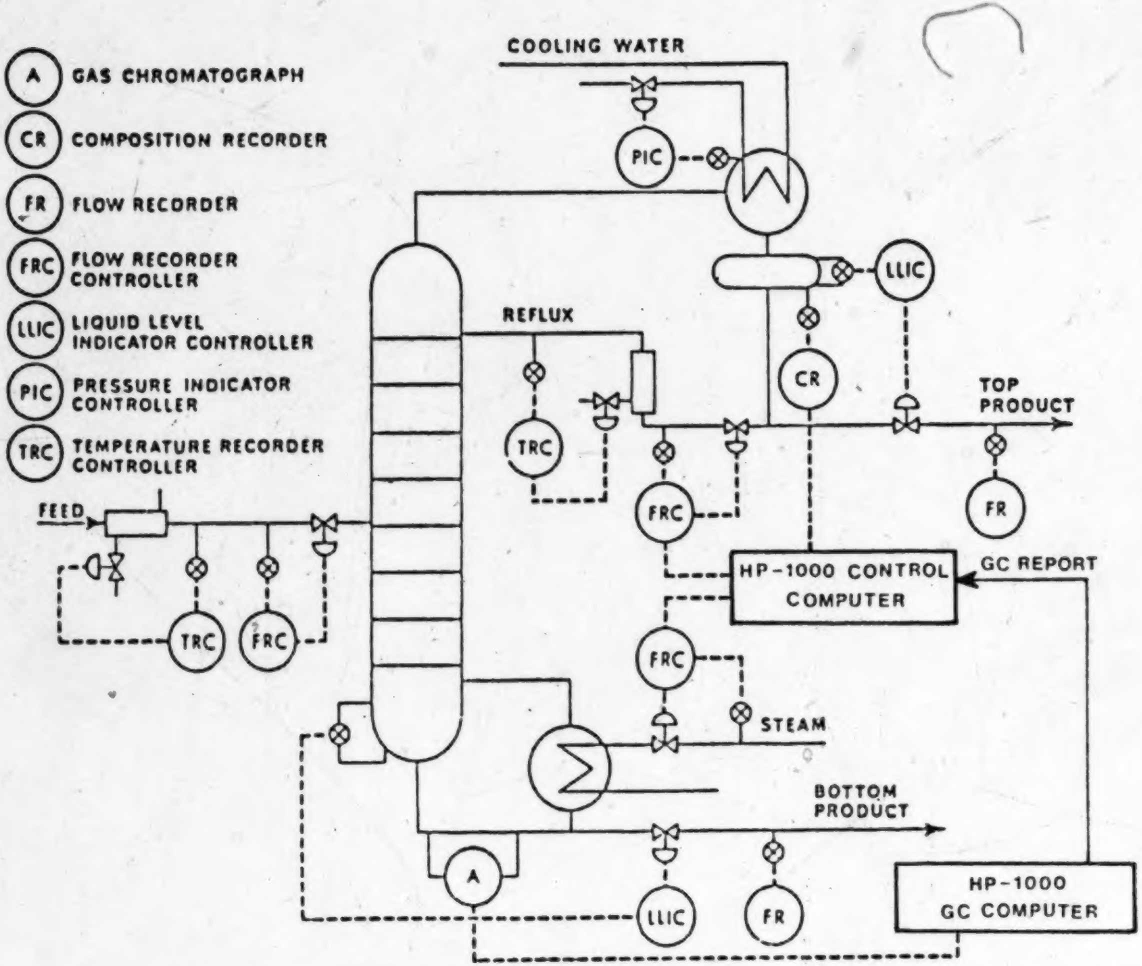
A GAS CHROMATOGRAPH
CR COMPOSITION RECORDER
FR FLOW RECORDER
FRC FLOW RECORDER CONTROLLER
LLIC LIQUID LEVEL INDICATOR CONTROLLER
PIC PRESSURE INDICATOR CONTROLLER
TRC TEMPERATURE RECORDER CONTROLLER
COOLING WATER
PIC
LLIC
REFLUX
CR
TOP PRODUCT
TRC
FRC
FR
FEED
TRC
FRC
HP-1000 CONTROL COMPUTER
GC REPORT
FRC
STEAM
BOTTOM PRODUCT
A
LLIC
FR
HP-1000 GC COMPUTER

Figure 3.1 Schematic Diagram of the Distillation Column and Interface to Computers

control output to the valve directly. In the supervisory mode, the computer relays a set point to the local analog controller. The computer provides the 'master' loop and the analog controller becomes the 'slave' loop.

One advantage of supervisory control over DDC is that supervisory control can remove the undesirable effect caused by a nonlinear valve. If the control output is sent directly to a nonlinear valve, then the same change in valve position for different inital valve position will result in a different change in absolute flow. It follows that for the same deviation from different set points, the change in flow caused by the controller will be different. With supervisory control, the appropriate change in flow is calculated directly in the computer and sent to the flow controller. The required change in valve position will be subsequently determined by the analog controller. The result is that the same output will always produce the same change in the flow.

Another advantage with supervisory control is that the flow is held constant in between sample times so disturbances that affect the flow are immediately compensated for by the analog controller. With DDC, the control output is sent directly to the valve. If the valve position is held constant, pressure fluctuations between sample times can cause the flow to oscillate. Local control is advantageous in the event of computer failure.

However, supervisory control becomes less desirable when the response time of the slave loop is of the same magnitude as the sample time of the master loop. In this situation, the dynamics of the slave loop adds directly to that of the master loop hence causing the control response to deteriorate.

For the pilot plant distillation column, the response time of the flow loops is much less than the sample time of the composition loops. Typically, the analog controllers will bring the flows to the new set points within a few seconds which is significantly less than the sample time for the composition loops. So consequently, the supervisory mode is used in the experimental study.

3.2 CONTROL LAW IMPLEMENTAION

To evaluate the self-tuning controller (STC), the output response using STC will be compared to the response achieved using a well tuned PID compensator. The comparison will be made on how well the controllers maintain the terminal compositions when the feed rate is changed.

For the three term proportional-integral-derivative compensator, the PID option in the Distributed System and Control (DISCO) package is used. Details of the implementation of DISCO on the pilot plant distillation column and the PID algorithm, written in the integral form, are given by Kan [66]. The STC algorithm could not be implemented using the DISCO executive because of size restriction. As a result, a completely separate program had to be written to execute under the Real Time Executive operating in the HP 1000 mini-computer. A listing of the program is given in Appendix C. The STC algorithm used in the program is given by Equations (2.55) to (2.59).

4. SELECTION OF MANIPULATED VARIABLE

4.1 INTRODUCTION

Before undertaking the control study, the process output and control input pairs for the pilot plant distillation column were first chosen. The five variables that have to be controlled are: top composition, bottom composition, column pressure, level in the reflux drum and level in the reboiler. The five available manipulated variables are: reflux flow, distillate flow, bottom product flow, heat input to the reboiler and heat removal by the condenser. The variables feed temperature, reflux temperature and feed composition will be kept constant for this study.

There are various configurations for pairing the controlled and manipulated variables. The two types of strategies that have been used most frequently are the schemes termed material balance control and energy balance control [67]. With the energy balance scheme, the pressure of the column is controlled by manipulating the cooling load in the condenser. The two drum levels are maintained by changing the respective output flows. The top composition is controlled by the reflux flow while bottom composition is controlled by boilup rate. The term energy balance originates because the terminal compositions of the column are controlled by changing the energy balance of the system and it is clear that reflux flow and reboiler load changes will directly affect the energy balance of the column.

With material balance control, the terminal composition is controlled by directly altering the material balance of the distillation column. One of the product flow rate is manipulated to control its own composition. Level for that end of the column is then controlled by either reflux flow or reboiler load depending on which product flow rate is used. The remaining variables will be paired the same way they are matched in the heat balance stratery.

Distillate flow is usually selected to control the material balance. The reason for this is that problems could develop if the the reboiler level is to be controlled by manipulation of the reboiler load. As the distillate flow is usually used, the ensuing discussion on material balance control will be based on using distillate flow to control the top composition. Analogous arguments can be given that will be applicable to the case when the bottom composition is controlled by manipulating bottom product flow rate. Schematic diagrams of the overhead composition control configuration for the material and energy balance control schemes are shown in Figures 4.1 and 4.2.

The concept of 'floating' the reflux flow on level control is not an easy one to accept since basic to the distillation column design procedure is the assumption of the operation at a constant reflux flow and fixed reflux ratio. Nevertheless, studies on different distillation columns have shown that the use of the material balance

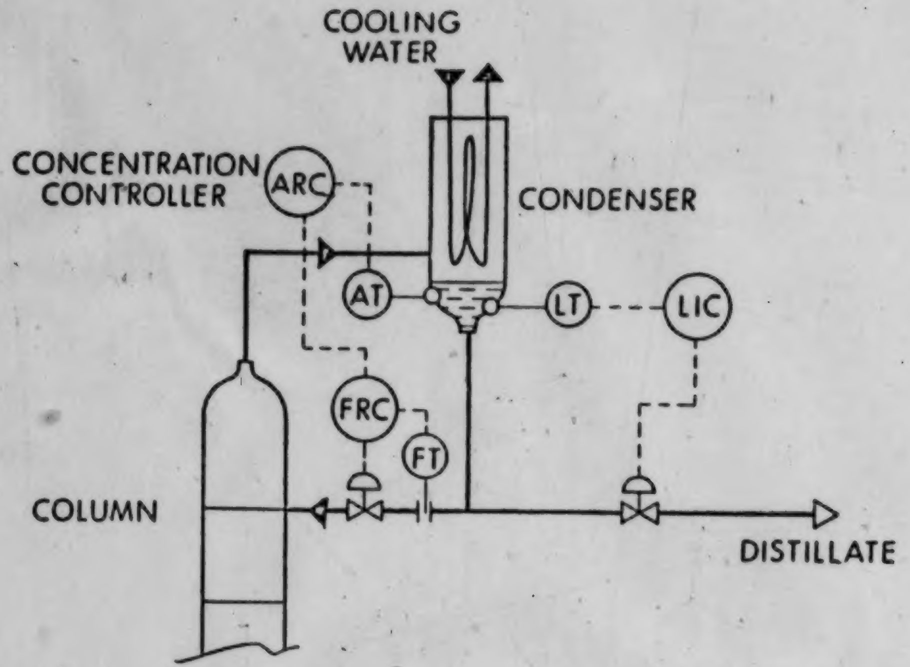
COOLING WATER
CONCENTRATION CONTROLLER
ARC
CONDENSER
AT
LT
LIC
FRC
FT
COLUMN
DISTILLATE

Figure 4.1 Schematic Diagram of the Energy Balance Control Scheme

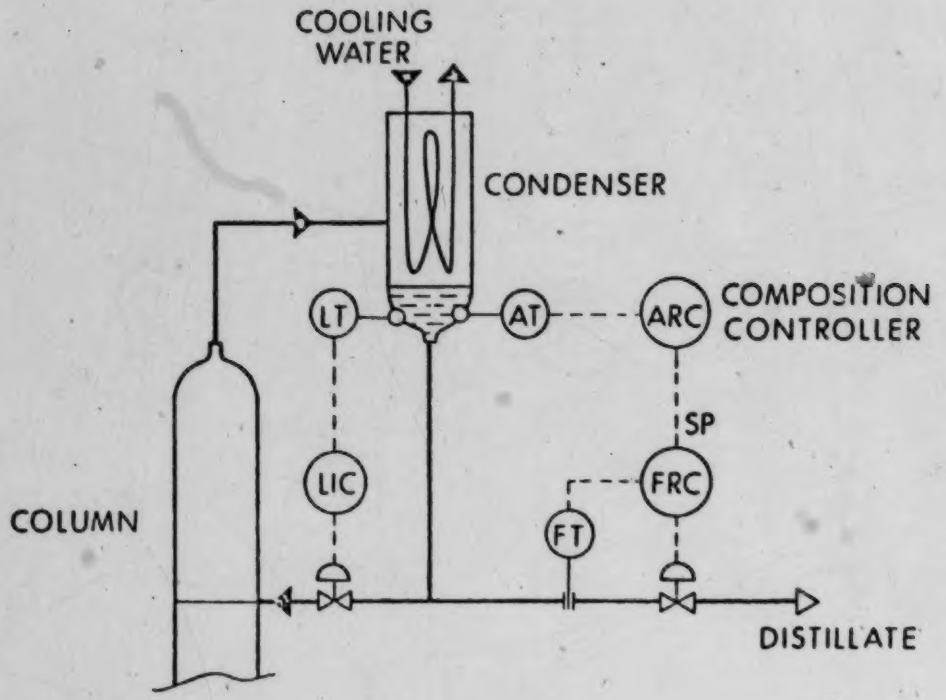
COOLING WATER
CONDENSER
LT
AT
ARC
COMPOSITION CONTROLLER
SP
LIC
FRC
FT
COLUMN
DISTILLATE

Figure 4.2 Schematic Diagram of the Material Balance Control Scheme

control scheme can result in improved control behaviour over the case when energy balance control is used [68-73]. In certain cases, it has been found that it is not possible to stabilize control without using the material balance approach [72,73]. In both cases, control of the overhead composition could not be realized by direct manipulation of reflux flow because of the very high external reflux ratio (greater than 25).

The main advantage of the material balance strategy is that it exhibits inherent reflux control when an energy disturbance is encountered because the reflux flow readjusts itself before any action is taken by the composition controller. This is accomplished because an energy disturbance will change the vapor rate in the column. As the new vapor rate reaches the condenser, the reflux drum level starts to change. Since the reflux flow is used to control the level, it will be adjusted to maintain level set point. The overall result is that reflux flow will change in the same direction as the change in vapor rate. Since the scheme inherently handles heat disturbances, material balance control reduces the interaction that occurs during simultaneous control of top and bottom composition. Variations in the reboiler load due to the bottom composition controller are treated as heat disturbances by the overhead controller so the reflux flow will be adjusted in the appropriate direction before any change in overhead composition is detected.

Other advantages of the material balance scheme are the following:

a. For the case where the reflux ratio is very large, using the distillate flow to control the reflux drum level can be very difficult. Since the distillate flow rate is much lower than the reflux flow, a large percentage change in distillate flow is required to compensate for small percentage changes in reflux flow. These large swings in distillate flow can be a big problem especially in situations where the distillate product is a feed to another column. Additional drum capacity might be needed to damp out the variation.

b. The material balance stratery is readily adapted for feedforward application since the required distillate to feed ratio can be determined exactly from the material balance relationship. Thus, the necessary change in distillate flow to compensate for changes in feed flow rate and feed composition can be easily calculated and subsequently fed forward through the appropriate dynamic compensator.

c. The material balance scheme will not exhibit a transient inverse response that is sometimes observed when reflux flow is directly used to control overhead composition. The inverse reponse as explained by Rosenbrock [74] is caused by plate overflow when an increased vapor rate first reaches the top of the distillation column. The overflow acts as an increased reflux flow hence causing the composition to initially become richer in the more volatile component. When the overflow stops, the increased vapor rate takes over and the composition becomes leaner in the more volatile component. With material balance control, the increased vapor rate would cause the reflux to increase and as a result, the inverse response should not occur.

The main disadvantage of the material balance strategy over the heat balance control case is the addition of the control dynamics of the level loop into the dynamics of the composition loop. When the top composition varies from the set point, the distillate flow is first adjusted. This change in turn affects the level in the reflux drum. Subsequently, the reflux flow then adjusts to maintain the drum level. The composition will not begin to change until the reflux flow has been changed. The overall result is that more dynamics is added hence slowing the response of the overhead composition loop. Futhermore, controller response to set point changes could be slower than the case when the reflux is adjusted directly.

4.2 ANALYSIS OF INTERNAL REFLUX RATIO SENSITIVITY TO HEAT DISTURBANCE

The self-regulation of the reflux flow in material balance control will lead to improved control performance only if the change in reflux flow is changed in a way which maintains the internal reflux ratio. Clearly, it is the maintenance of the internal reflux ratio that allow the material balance scheme to be less sensitive to heat disturbances. By holding a constant internal reflux ratio, the slope of the operating curve remains unchanged hence the composition is unaltered.

For a distillation column operating with a large external reflux ratio, a material balance strategy will maintain the internal reflux ratio better than the energy balance case. However, if the external reflux ratio is low, the self-regulating change in reflux flow can cause the internal reflux ratio to vary more than the energy balance scheme. The best way to illustrate the effect is a simple numerical example. It should be noted that in the ensuing analysis, the V/L ratio will be considered instead of L/V traditionally defined as the internal reflux ratio. The reason for this is that the region of interest is for internal reflux ratio less than 1. The reciprocal, V/L, will have a greater numerical range.

Consider a situation where the external reflux ratio is 10.0, that is:

$$\frac{\text{Reflux Flow (L)}}{\text{Distillate Flow (D)}} = 10.0 \qquad (4.1)$$

or,

$$L = 10.0D \tag{4.2}$$

Since the vapor rate (V) is given by:

$$V = L + D \tag{4.3}$$

Combining Equation (4.2) and (4.3) yields:

$$V = 11.0D \tag{4.4}$$

and the resulting ratio is:

$$\frac{V}{L} = \frac{11.0D}{10.0D} = 1.1 \tag{4.5}$$

Suppose that the column is subjected to energy disturbances that correspond to a required change in the vapor rate of a 20% increase and a 20% decrease. The required new V/L ratio for both material balance and energy balance stratergies for such changes are given in Table 4.1. Recall that for material balance control, the reflux flow will change by the same amount the vapor rate is changed. From Equation (4.4), a 20% change in vapor rate is:

$$0.2V = 0.2 * 11.0D = 2.2D \tag{4.6}$$

It is evident from the values in Table 4.1 that the material balance control clearly maintains a more constant V/L ratio than the heat balance case as the ratio under the material scheme changes less than 3% compared to the 20%

changes for the energy balance case.

Table 4.1 Variation of V/L with Control Scheme for ±20% Changes in Vapor Rate at an External Reflux Ratio of 10.0

Control Scheme	Positive Disturbance	Deviation From S.S.	Negative Disturbance	Deviation From S.S
Material Balance	$\frac{11.0+2.2}{10.0+2.2} = 1.08$	-1.6%	$\frac{11.0-2.2}{10.0-2.2} = 1.13$	+2.6%
Energy Balance	$\frac{11.0+2.2}{10.0} = 1.32$	+20.0%	$\frac{11.0-2.2}{10.0} = 0.88$	-20.0%

Now, consider the case when the external reflux ratio is only 1.0, that is:

$$\frac{L}{D} = 1.0 \qquad (4.7)$$

so,

$$V = L + D = 2.0D \qquad (4.8)$$

and the steady value of V/L is:

$$\frac{V}{L} = \frac{2.0D}{D} = 2.0 \qquad (4.9)$$

The new V/L ratios that result from ±20% changes in vapor rate are given in Table 4.2.

Table 4.2 Variation of V/L with Control Scheme for ±20% Changes in Vapor Rate at an External Reflux Ratio of 1.0

Control Scheme	Positive Disturbance	Deviation From S.S.	Negative Disturbance	Deviation From S.S
Material Balance	$\frac{2.0+0.4}{1.0+0.4} = 1.71$	-14.3%	$\frac{2.0-0.4}{1.0-0.4} = 2.67$	+33.3%
Energy Balance	$\frac{2.0+0.4}{1.0} = 2.40$	+20.0%	$\frac{2.0-0.4}{1.0} = 1.60$	-20.0%

As can be seen from the numerical values in Table 4.2, which are markedly different from those in Table 4.1, the material balance control scheme is preferable for a postive disturbance but just the reverse for the negative disturbance. Cleary, for a situation where the external reflux ratio is 1.0, the energy balance strategy will prove to be less sensitive to heat disturbances. The choice of energy balance control becomes even more advantageous if it is recalled that with the energy balance scheme, the dynamics of the reflux drum level do not enter the overhead composition control loop.

These simple numerical calculations have clearly illustrated that the material balance control scheme will not always be superior to heat balance control with the choice of scheme dependent on the external reflux ratio. While it is true that most industrial columns operate with an external ratio much greater than one, that is not necessarily the case with pilot plant distillation columns. In this study, the pilot plant column operating conditions are:

Reflux Flow = 10.2 g/s
Distillate Flow = 8.8 g/s

so, the steady state V/L ratio is:

$$\frac{V}{L} = \frac{10.2 + 8.8}{10.2} = 1.87$$

The change in the V/L ratio for ±20% changes in the vapor rate are shown in Table 4.3.

Table 4.3 Variation of V/L with Control Scheme for ±20% Changes in Vapor Rate

Control Scheme	Positive Disturbance	Deviation From S.S.	Negative Disturbance	Deviation From S.S.
Material Balance	$\frac{19.0+3.8}{10.2+3.8} = 1.63$	-12.6%	$\frac{19.0+3.8}{10.2-3.8} = 2.34$	+27.6%
Energy Balance	$\frac{19.0+3.8}{10.2} = 2.24$	+20.0%	$\frac{19.0-3.8}{10.2} = 1.49$	-20.0%

The results presented in Table 4.3 indicate that the reduced deviation with the material balance control compared to energy balance control for a positive disturbance (7.4% lower deviation) is just about equal to the higher deviation of 7.6% for the negative disturbance. As both stratergies are equally sensitive to heat disturbances, heat balance control is the strategy chosen because the material balance scheme has the added disadvantage of having a slower response due to the inclusion of the condenser level dynamics.

4.3 EXPERIMENTAL OPEN LOOP RESPONSES

To substantiate the analysis carried out in the previous section, experimental open loop responses where obtained for the top and bottom compositions to changes in steam flow using both the material balance and energy balance configurations. The steam flow changes simulated heat disturbances entering the system.

For each control strategy, steam flow rate was increased and decreased to flow rates representing a change of 7 1/2% from its steady state value. The open loop responses for the material balance scheme are shown in Figures 4.3 and 4.4. The corresponding responses for energy balance control are shown in Figures 4.5 and 4.6. The results are summarized in Table 4.4.

Table 4.4 Top and Bottom Composition Changes to Steam Flow Rate Disturbances.

	7 1/2% Increase In Steam Flow Rate		7 1/2% Decrease in Steam Flow Rate	
Control Scheme	XD Change	XB Change	XD Change	XB Change
Material Balance	+0.82%	-0.55%	-1.32%	+1.32%
Energy Balance	-1.50%	-4.08%	+0.58%	+6.57%

The results of Table 4.4 are in agreement with the predictions given by the analysis of the vapor-to-liquid ratio for vapor rate changes. The values in Table 4.3 indicate that the overhead composition should be more sensitive to a positive energy disturbance when the energy balance scheme is used than if material balance control is used. This is indeed the case as can be seen from the 1.5% decrease in overhead composition with energy balance control compared to the 0.82% increase under the material balance scheme. The results for the negative disturbance are also consistent with those in Table 4.3 since the top composition decreases by 1.32% for material balance control but only increases by 0.58% for energy balance control.

The potential advantage of the material balance scheme for systems with a large external reflux ratio is illustrated by considering the bottom composition. Since the entering feed is a liquid, the liquid rate below the feed

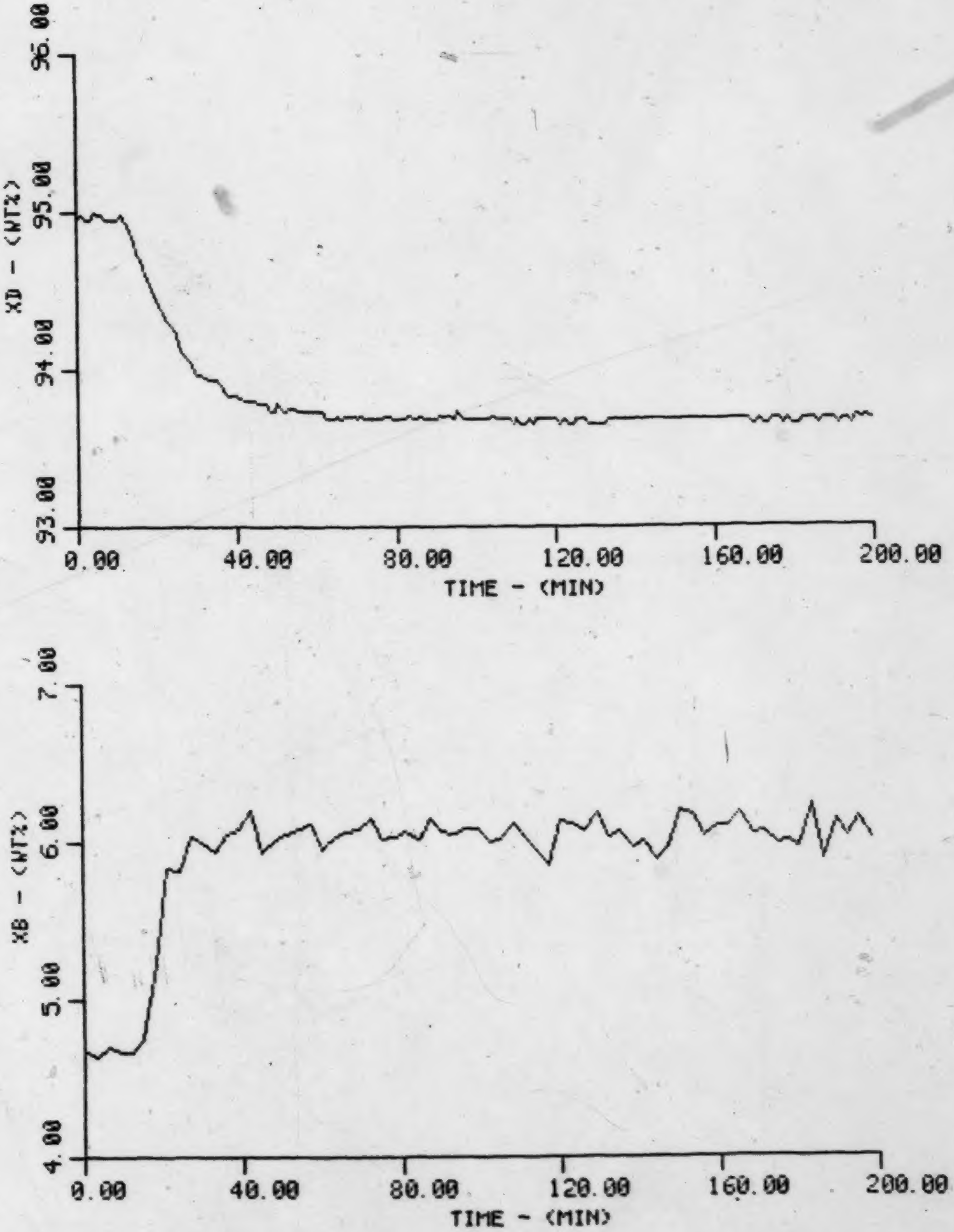

Figure 4.3 Open Loop Response to a 7 1/2% Step Decrease in Steam Flow With A Material Balance Configuration

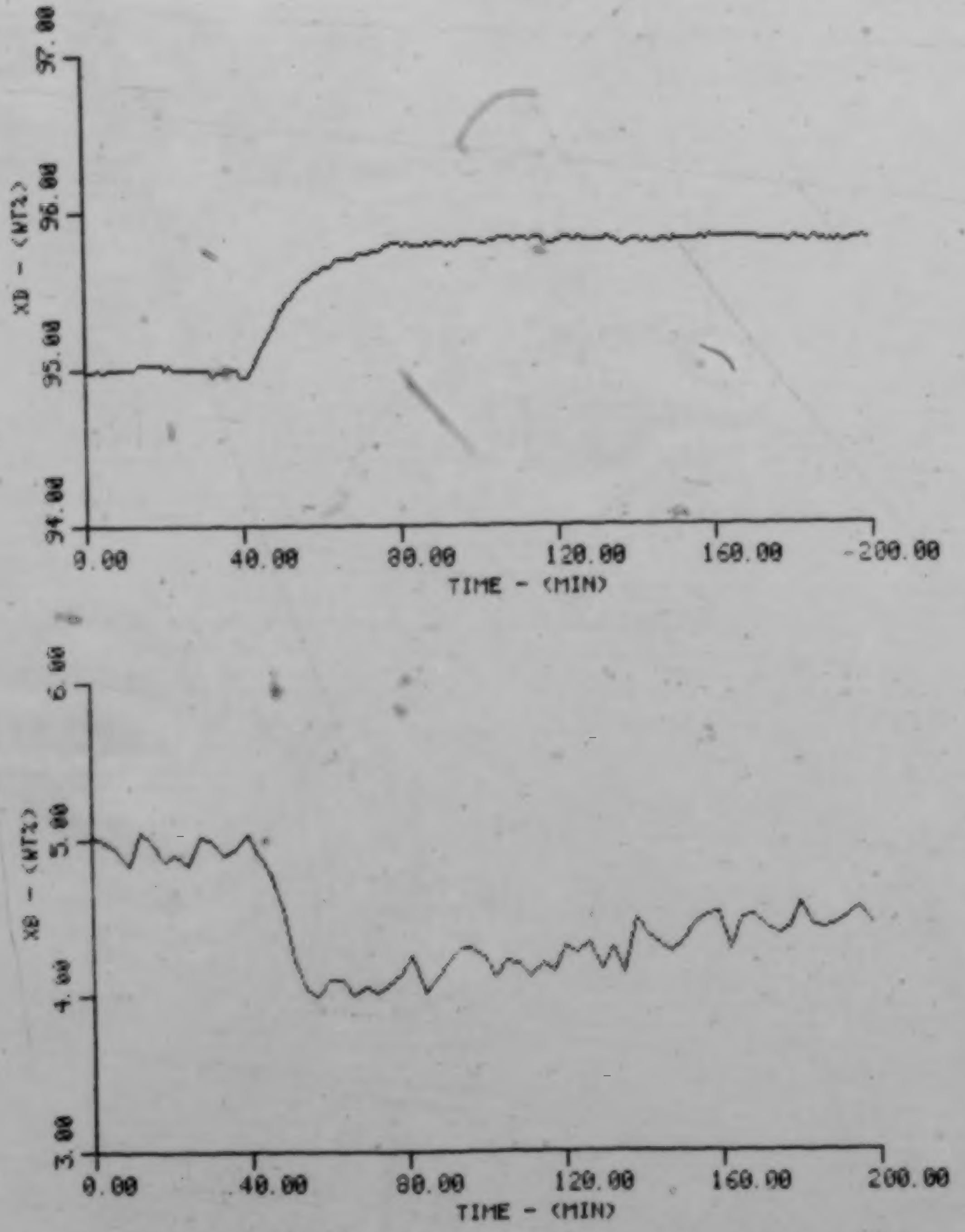

Figure 4.4 Open Loop Response to a 7 1/2% Step Increase in Steam Flow With A Material Balance Configuration

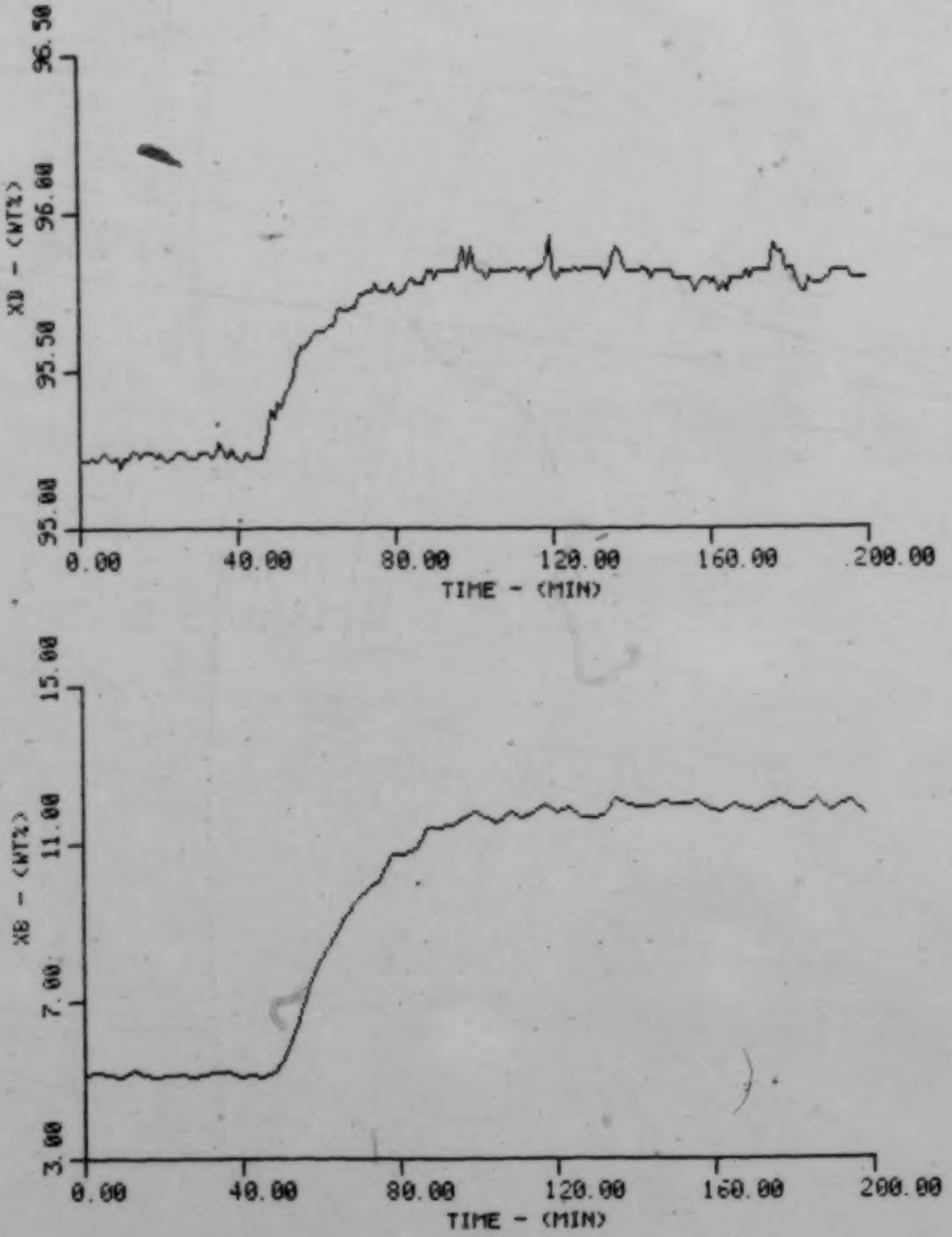

Figure 4.5 Open Loop Response to a 7 1/2% Step Decrease in Steam Flow With an Energy Balance Configuration

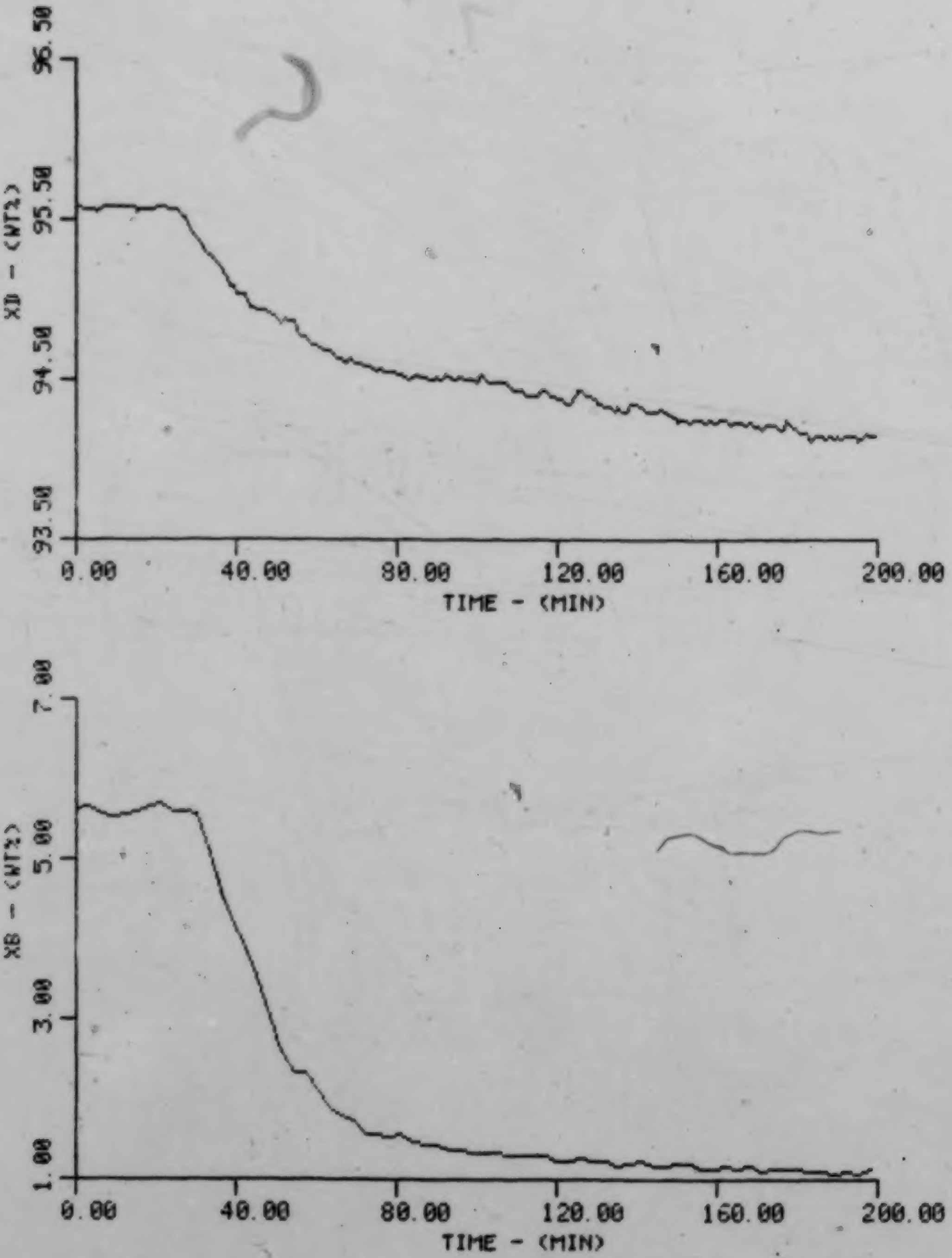

Figure 4.6 Open Loop Response to a 7 1/2% Step Increase in Steam Flow With an Energy Balance Configuration

plate is increased substantially. In effect, more reflux is being added to the column. From the results of Table 4.1, it should follow that the vapor-to-liquid ratio and hence the bottom composition should be less sensitive to heat disturbances if material balance control is used. This is in fact the situation observed. For both positive and negative disturbances, there is a more significant change in the bottom composition with the energy balance configuration than with material balance control. For the positive disturbance, the composition change with energy balance control is 7 1/2 times larger than the change with material balance control.

4.4 CONCLUSION

Material balance control is shown to be superior to energy balance control for the case of a large external reflux ratio while with smaller reflux ratio it will be more advantageous to use the energy balance scheme. Comparison of the change in the vapor-to-liquid ratio for the same change in vapor rate for both control schemes can help to decide which strategy should be used for a given situation.

For the column operating conditions, analysis of the vapor-to-liquid ratio for vapor rate changes and subsequent experimental verification have shown that the choice of control strategy depends on the type of disturbance. Energy balance control is less sensitive to a negative energy disturbance but because the material balance control scheme inherently includes condenser level dynamics, the energy balance scheme is employed in this study.

5. EXPERIMENTAL RESULTS

5.1 INTRODUCTION

This chapter presents the results of the experimental runs that have been carried out on the distillation column using the PID and self-tuning controllers. A brief discussion of the experimental procedures and the actual programs that were used will be given. The results are presented in the following order:

a. PID runs for top composition, bottom composition and dual composition control;
b. STC runs for top composition control;
c. STC runs for bottom composition control;
d. STC runs for dual composition using multiloop configuration (ML-STC);
e. STC runs for dual composition using multivariable configuration (MV-STC).

Control of top product composition will be used to study most of the properties of the self-tuning controller while bottom composition will be used to evaluate the feedforward (FF) feature of the STC.

5.2 EXPERIMENTAL PROCEDURE

Four types of disturbances were used to perturb the distillation column:

a. a 25% reduction in feed flow rate;
b. a subsequent feed flow rate increase to return the

rate to its normal steady state flow;

c. a 25% increase in feed flow rate;

d. a subsequent feed flow rate decrease to return the rate to its normal steady state value.

For the study of top composition control, the disturbances of a 25% increase in feed flow rate and the subsequent return of the flow rate to its steady state value were not used because the top composition showed virtualy no change for these disturbances as can be seen from the responses in Figures 5.1 and 5.2 (The arrow in the figures indicate the time that the step change in feed flow rate is introduced). In addition, only a limited number of multiloop and multivariable runs were performed for these two disturbances because a condition of flooding nearly resulted when the feed rate was increased 25% above the steady state flow rate.

With single loop control, the self-tuning controller was started with zero initial parameter estimates and the initial $\underline{\underline{P}}^c$ matrix is set at $1000\underline{\underline{I}}$ to show that there was lack of confidence in the initial estimates. The controller was given time to obtain reasonable estimates before a feed disturbance was introduced. For the multiloop and mutivariable configuration, the self-tuning controller was started with the final estimates obtained from the single loop control tests. To show that there was confidence in these estimates, the initial $\underline{\underline{P}}^c$ matrix was set equal to $.01\underline{\underline{I}}$. As with the single loop control case, the parameters

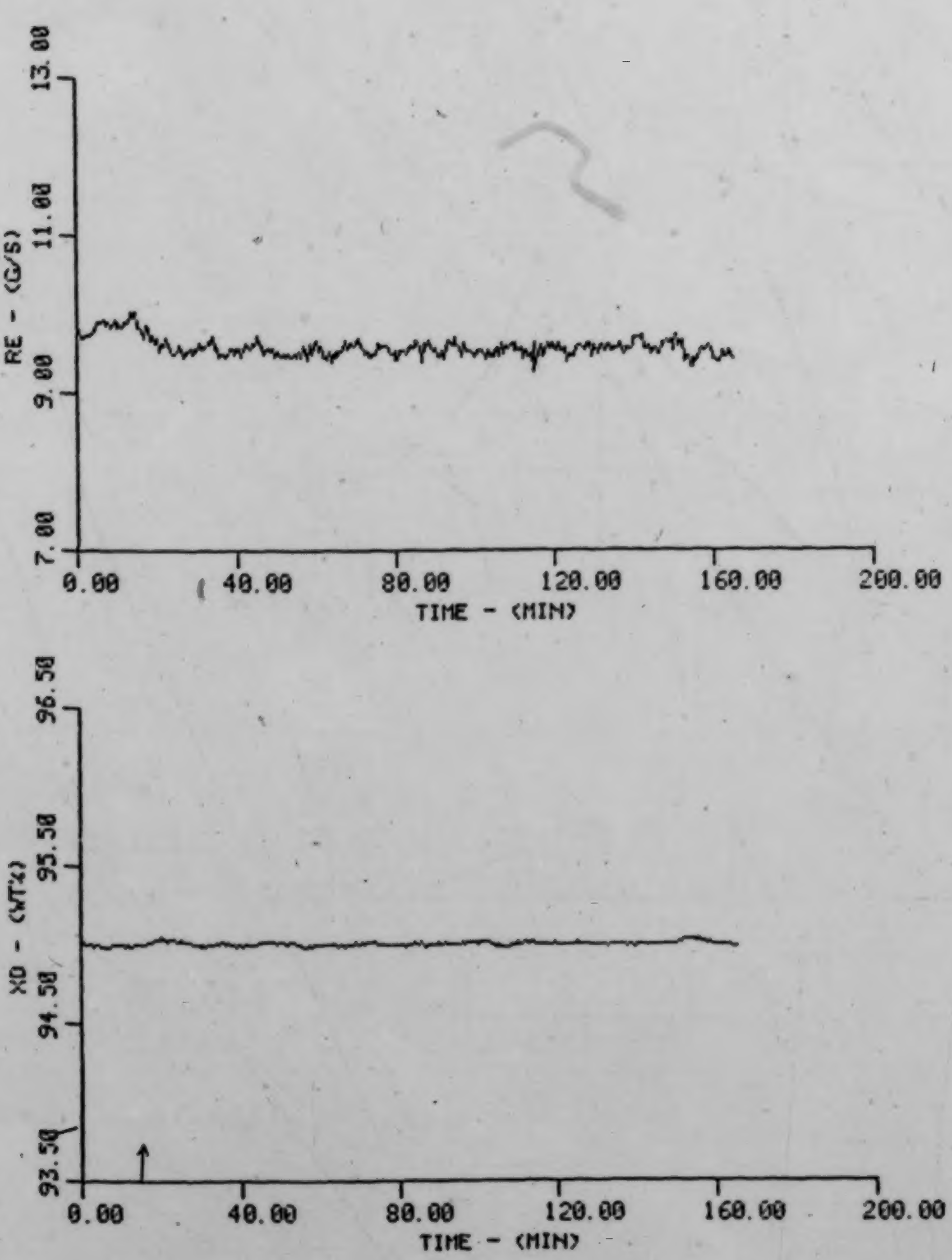

Figure 5.1   PID Control of Top Composition for a +25% Step Change in Feed Flow Rate

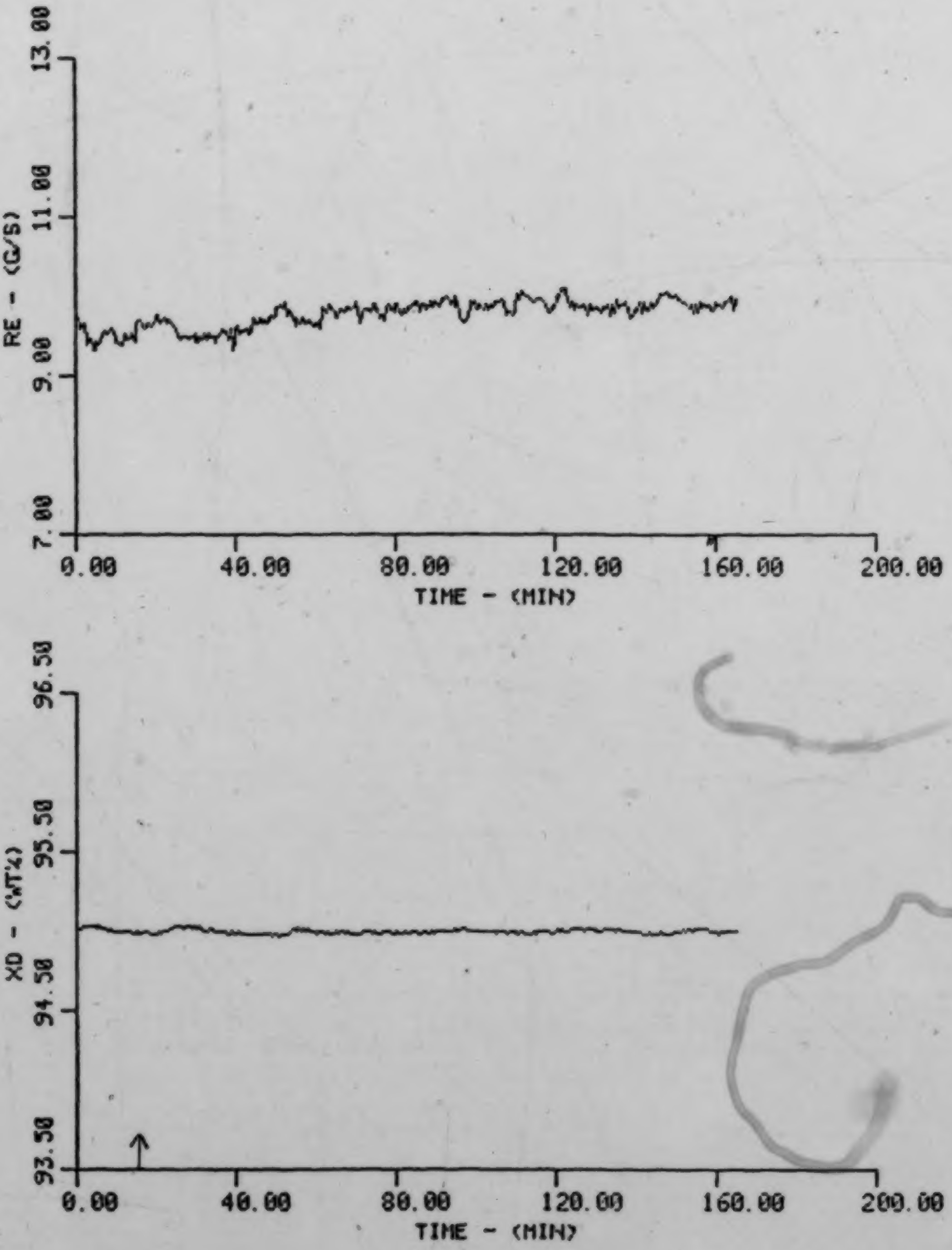

Figure 5.2 PID Control of Top Composition for a Step Decrease in Feed Flow Rate to its Normal Steady State Value

were allowed to converge before a feed change was made. When comparing the control performance of the self-tuning controller with that of the PID controller, only STC runs for which the disturbance is introduced after the initial identification are considered

The discussion given in Section 2.3.1 has shown that the self-tuning controller can be thought of as a feedback controller with a discrete compensator which uses the predicted output instead of the measured output as the feedback signal for control action. From Equation (2.23), it can be seen that the discrete compensator is equal to the inverse of the Q-weighting (Q-WT). By selecting the inverse of the Q-weighting to be the PI controller and assuming the predicted output to be correct, standard techniques proposed by Verbruggen et al. [75] can be used to obtain an initial choice for the PI constants based on the open loop response. Since the predicted output is used, the PI constants are those based on the system except for the effect of the process time delay.

For the single loop control tests, the constants obtained from the method based on the open loop responses produced good control but it was found that increasing the integral gain improved the control response. For the multiloop and multivariable cases, a certain amount of de-tuning was necessary to prevent oscillatory responses.

Experience with tuning the Q-weighting showed that the response was not as sensitive to variation in the

Q-weighting parameters compared to the sensitivity of the PID compensator to changes in the PID constants. The reason for this insensitivity is due to the fact that the parameters change to compensate to some degree for changes in the Q-weighting constants. Although the sensitivity was different, it was found that the PI constants in the Q-weighting could be tuned in the same way a normal PI compensator is tuned; i.e., the relationship between the proportional and integral gains and how they affect the output response remains the same.

5.3 COMPUTER PROGRAMS

With the change of computer system in the DACS center, support programs for the distillation column had to be written for the new system. A monitor program, BDC99, was written to monitor key process variables on the column. When the values of the variables exceeds specified constraints, BDC99 will shut down the distillation column.

As discussed in chapter three, the chromatogram analysis is done by a computer seperate from the central computer where the other process measurements are available. As the control algorithm will execute in the central computer, a program, GCLNK had to be written to receive the report from the GC computer and transfer the information into some buffer in the central computer. Programs GCSCH and GCSWT then processed the information in the buffer to extract the value of the the bottom composition from the report. The programs also served to start the GC sample cycle at the appropriate time.

The implementation of the self-tuning control algorithm on the column was carried out with programs STC and HSET. Program HSET is used to alter the data file that contains the starting parameters and options used for the self-tuning controller while program STC contains the control algorithm. In addition to the algorithm itself, program STC takes care of storing the relevant variables in a disk file. When the STC program is executing, communication with the program can be accomplished through a group of digital switches. Utility programs HPLOT and ERSUM were written to provide plots and calculation of the sum of the absolute error (SAE) of the results stored in the data files for a user specified period of time (number of sampling intervals).

A listing of programs HSET and STC is included in Appendix C. A listing of the remaining programs is only included in certain copies of this work.

5.4 CONTROL BEHAVIOUR USING PID CONTROL

The control performance obtained using conventional PID control action will be used as the base case for evaluation of the self-tuning controller. For the three cases of: top composition control, bottom composition control and simultaneous product composition control, the PID results presented are for a well tuned PID compensator. While the performance cannot be guaranteed to have been obtained using true optimal tuned PID controller settings, the constants have been so well tuned that any changes in their values cause the control performance to deteriorate. The controller performance is measured by the sum of the absolute error (SAE). For top composition control, with a sampling time of 1 minute, the SAE is taken over one hour or 60 samples after the feed flow rate change. For bottom and dual composition control, with a sampling time of 3 minute, the SAE is taken over 1 1/2 hour period or 30 samples after the feed flow rate change.

For the single loop control test, the first choice of PID constants was obtained using the techniques proposed by Verbruggen et. al. [75] which bases the selection of PID constants on the system open loop response. Using these values as a starting point, the parameters were altered in a systematic way until further changes in the constants resulted in deterioration of the control performance. For the simultaneous control case, the well tuned single loop constants, reduced by one half were used as the initial choice. The constants were reduced because of the interaction between the top and bottom composition control loops.

The experimental results for top composition control are those given in Section 5.2 (cf. Figures 5.1 and 5.2) and in Figures 5.3 and 5.4. The bottom composition control results are shown in Figures 5.5 to 5.8. For bottom composition control, the PID constants are significantly

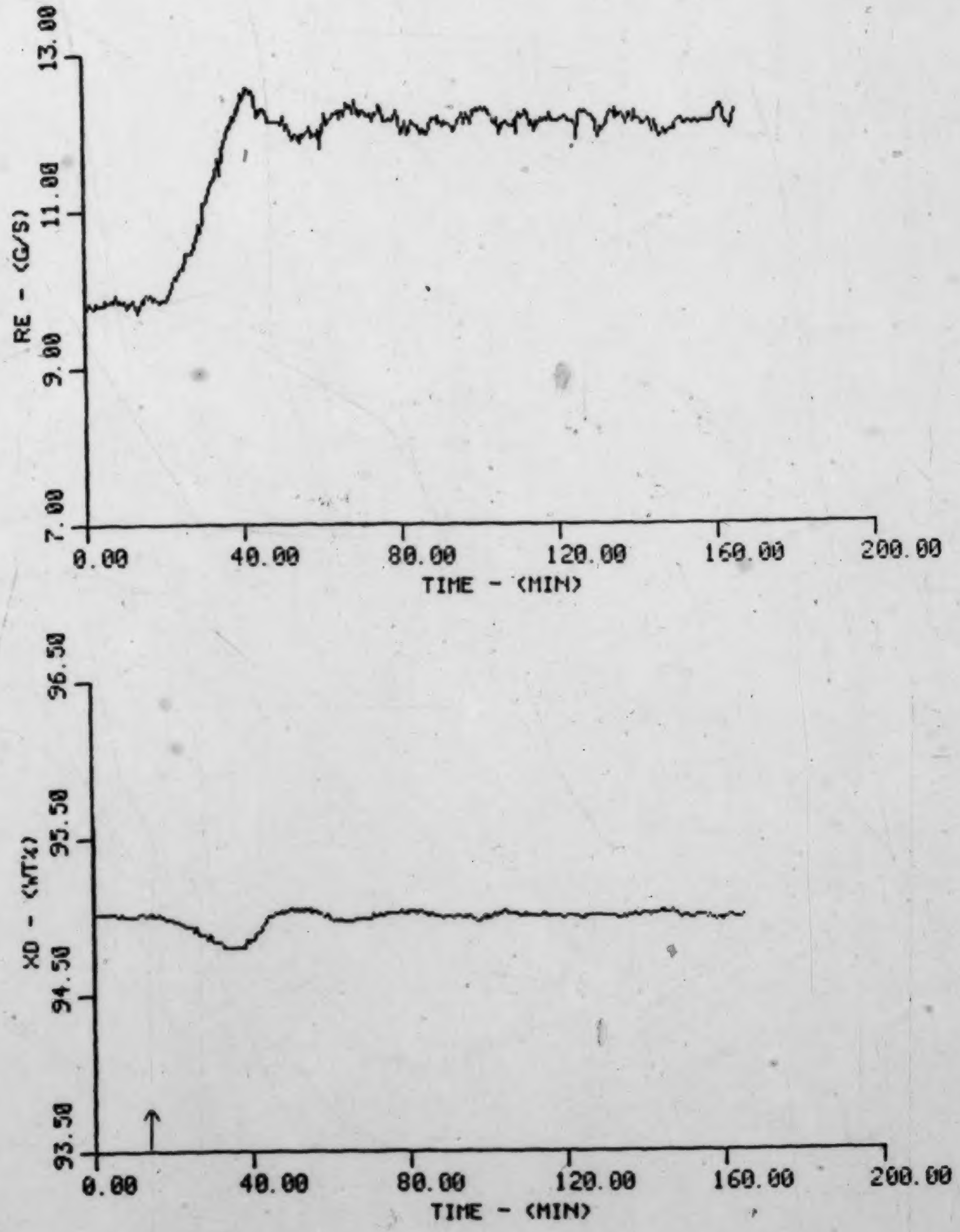

Figure 5.3 PID Control of Top Composition for a -25% Step Change in Feed Flow Rate

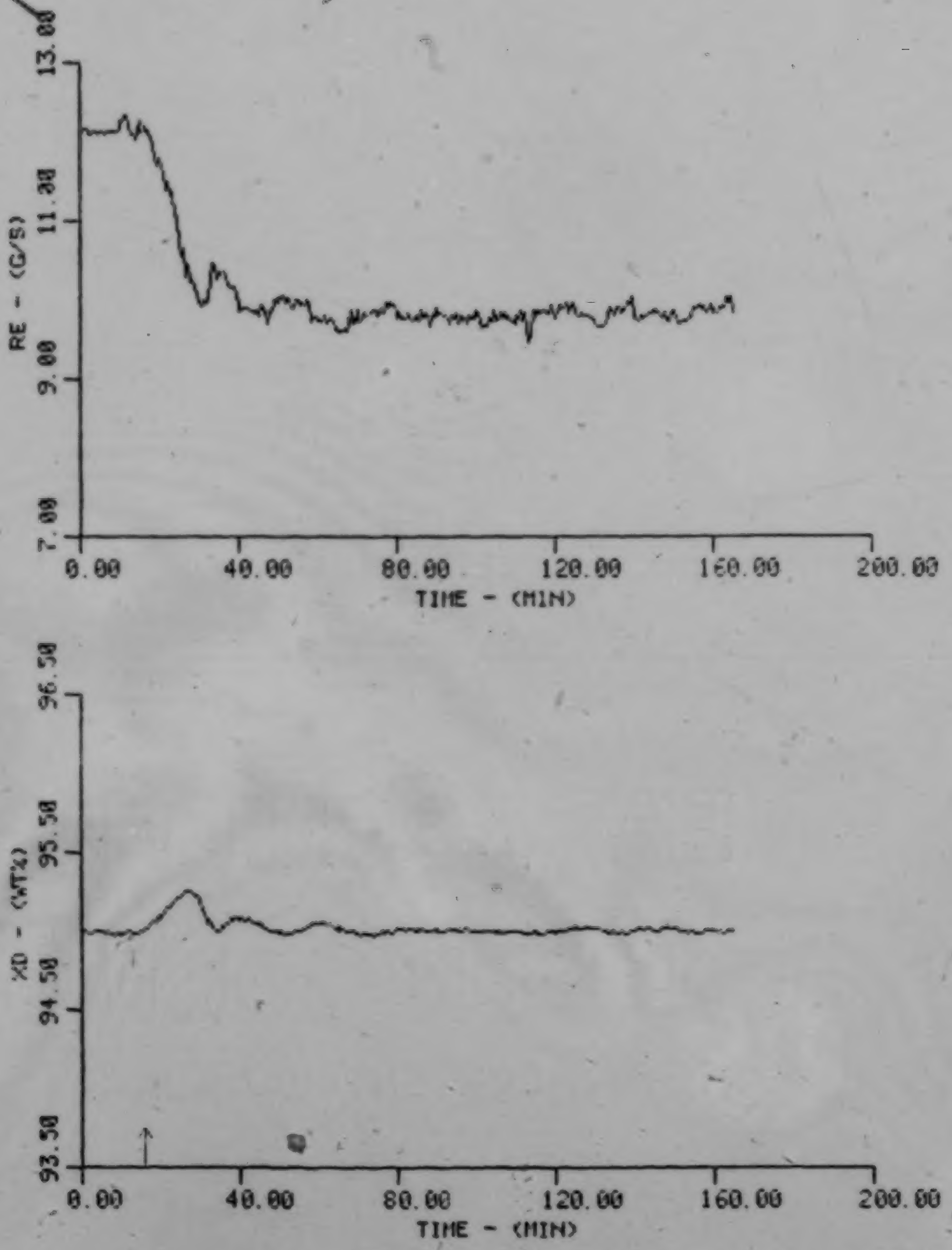

Figure 5.4 PID Control of Top Composition for a Step Increase in Feed Flow Rate to its Normal Steady State Value

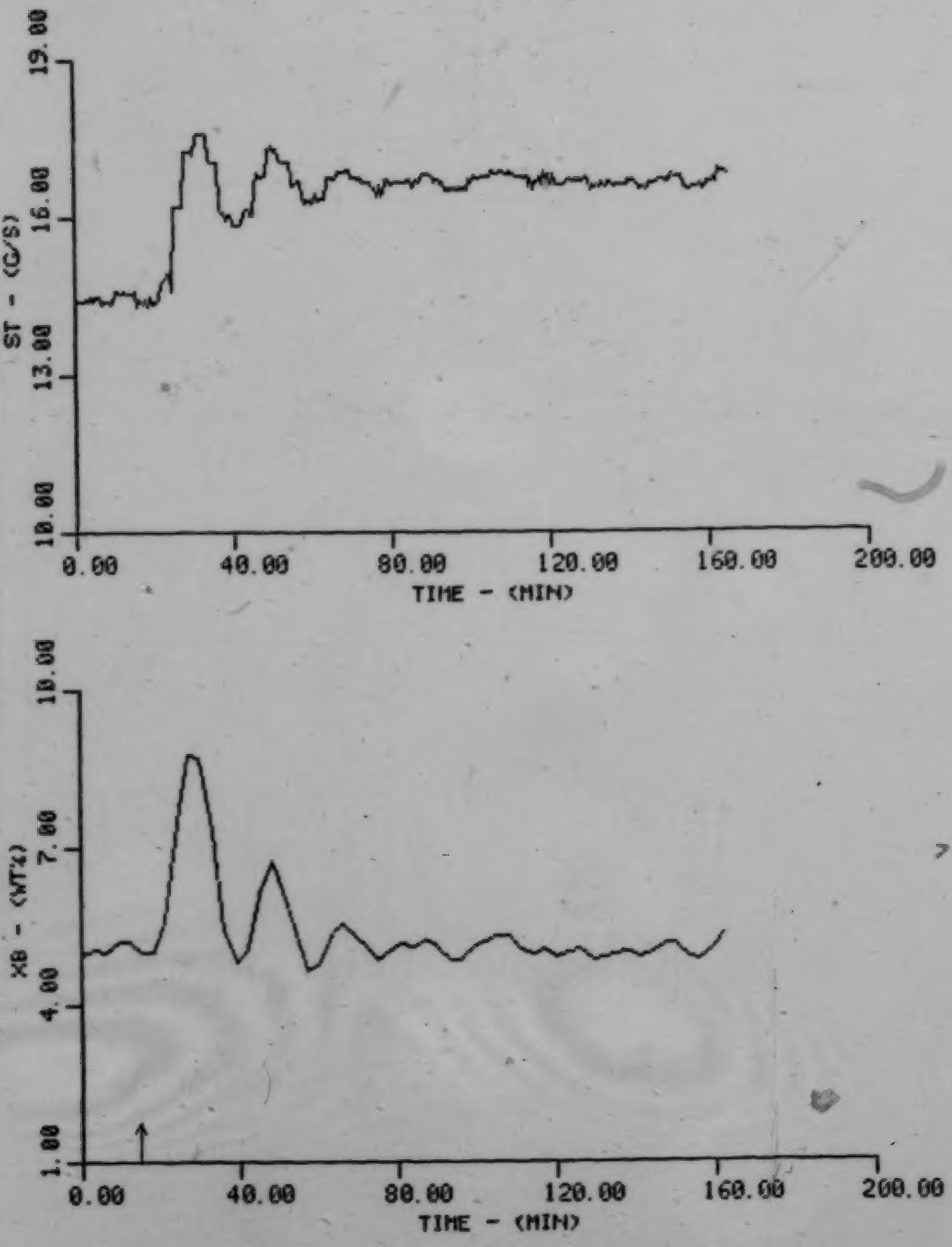

Figure 5.5 PID Control of Bottom Composition for a +25% Step Change in Feed Flow Rate

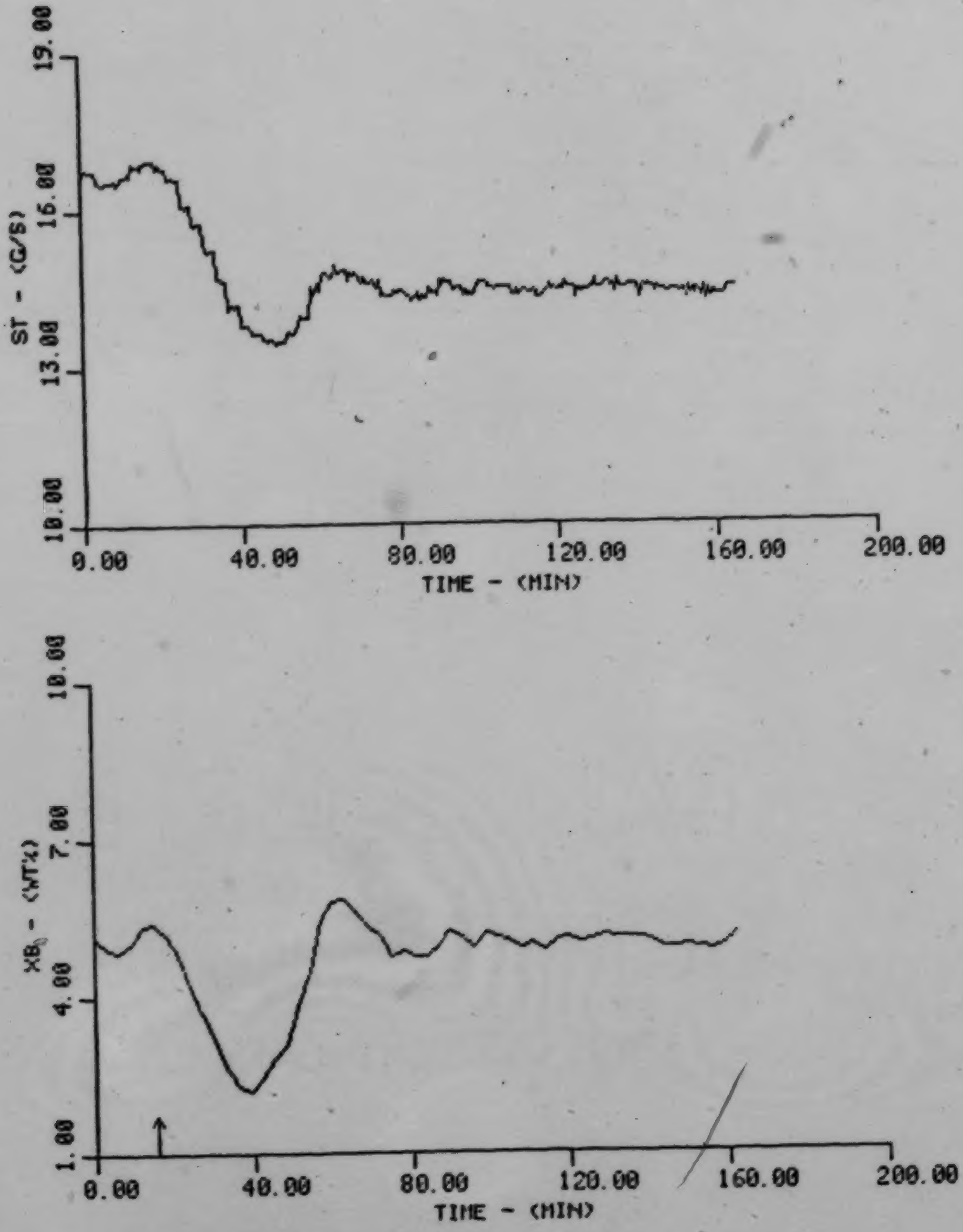

Figure 5.6 PID Control of Bottom Composition for a Step Decrease in Feed Flow Rate to its Normal Steady State Value

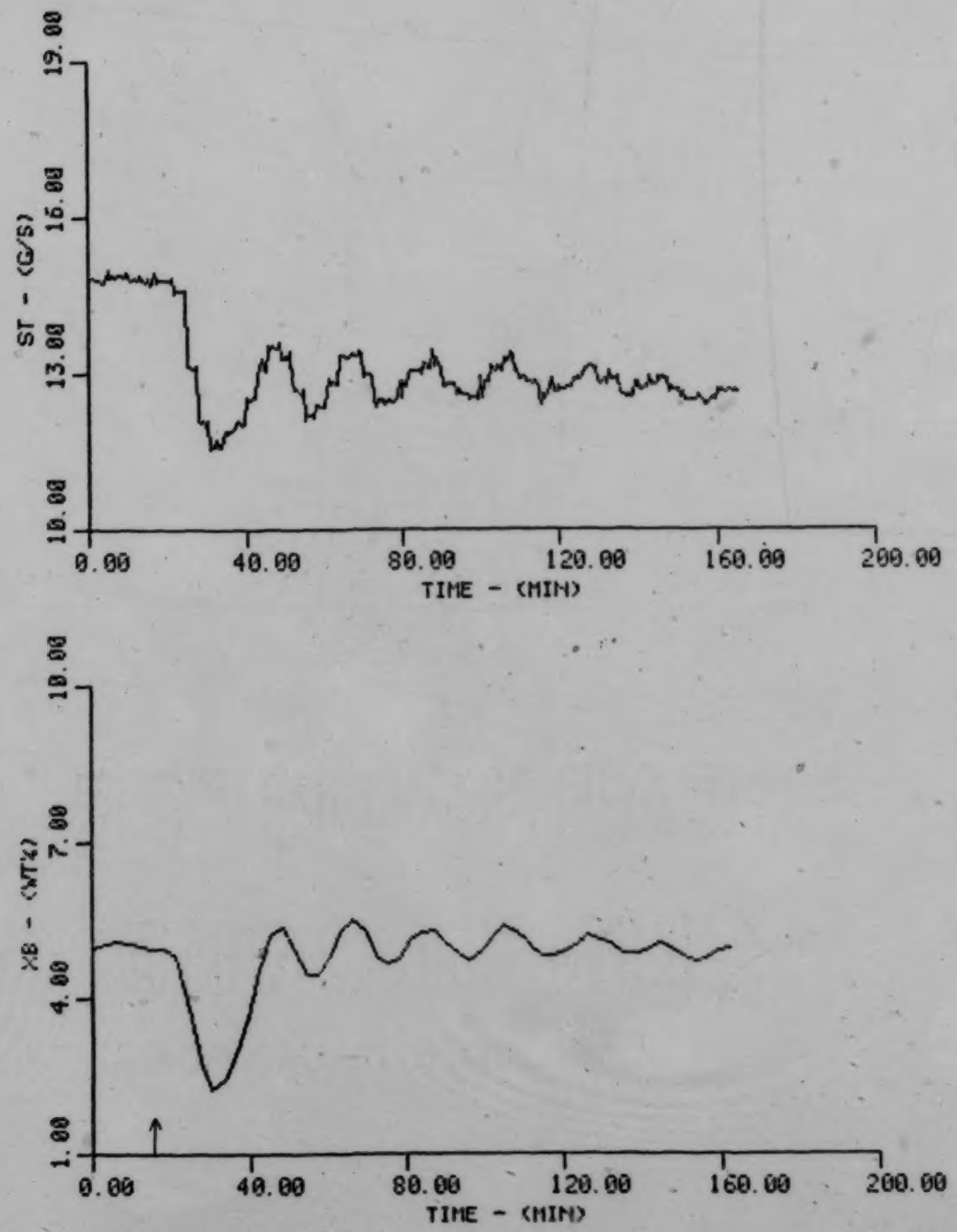

Figure 5.7 PID Control of Bottom Composition for a -25% Step Change in Feed Flow Rate

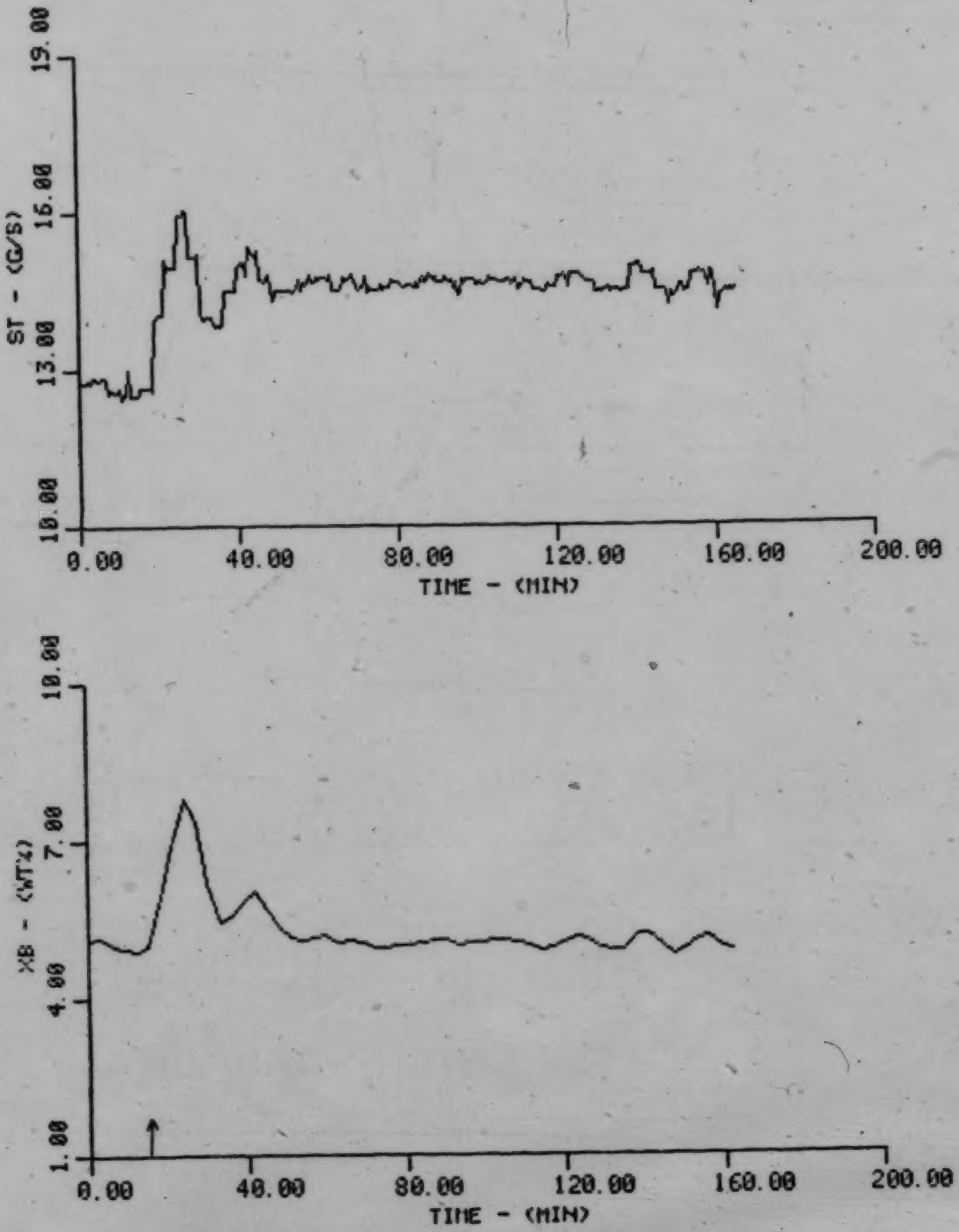

Figure 5.8 PID Control of Bottom Composition for a Step Increase in Feed Flow Rate to its Normal Steady State Value

different for the positive and the negative feed flow rate disturbances as can be seen from Table 5.1. This is due to the nonlinear dynamic characteristics of the column. The results for the dual composition control are shown in Figures 5.9 to 5.12. The PID constants are tuned on the basis of a -25% step change in feed flow rate only. A summary of the SAE for these results is given in Table 5.1.

Table 5.1 Summary of Absolute Error Values For PID Control

Type of Control	Type of Disturbance	Figure	SAE (wt%)	PID Constants K_p / K_i / K_d
Top	+25% to feed	5.1	0.460	2.81/0.73/0.65
Top	Return to S.S.	5.2	0.785	2.81/0.73/0.65
Top	-25% to feed	5.3	3.870	2.81/0.73/0.65
Top	Return to S.S.	5.4	3.410	2.81/0.73/0.65
Bottom	+25% to feed	5.5	20.72	-.50/-.13/-.08
Bottom	Return to S.S.	5.6	26.05	-.50/-.13/-.08
Bottom	-25% to feed	5.7	18.43	-.70/-.15/-.67
Bottom	Return to S.S.	5.8	14.00	-.70/-.15/-.67
			top / bot	
Dual	+25% to feed	5.9	2.75/27.3	top constants:
Dual	Return to S.S.	5.10	2.87/27.1	3.57/0.93/0.83
Dual	-25% to feed	5.11	2.13/21.7	bot constants:
Dual	Return to S.S.	5.12	2.30/23.0	-.58/-.13/-.13

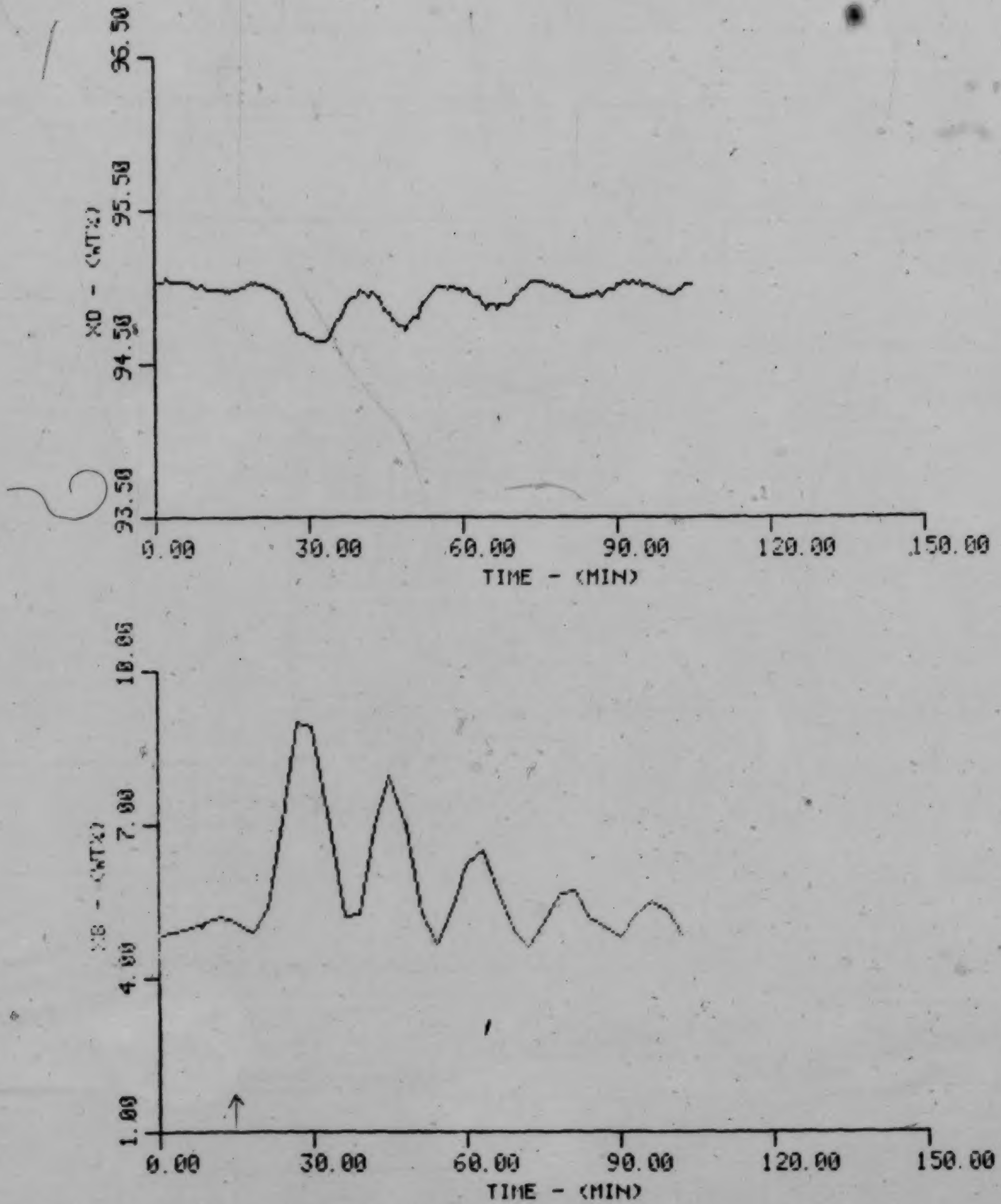

Figure 5.9 Multiloop PID Control of Terminal Compositions for a +25% Step Change in Feed Flow Rate

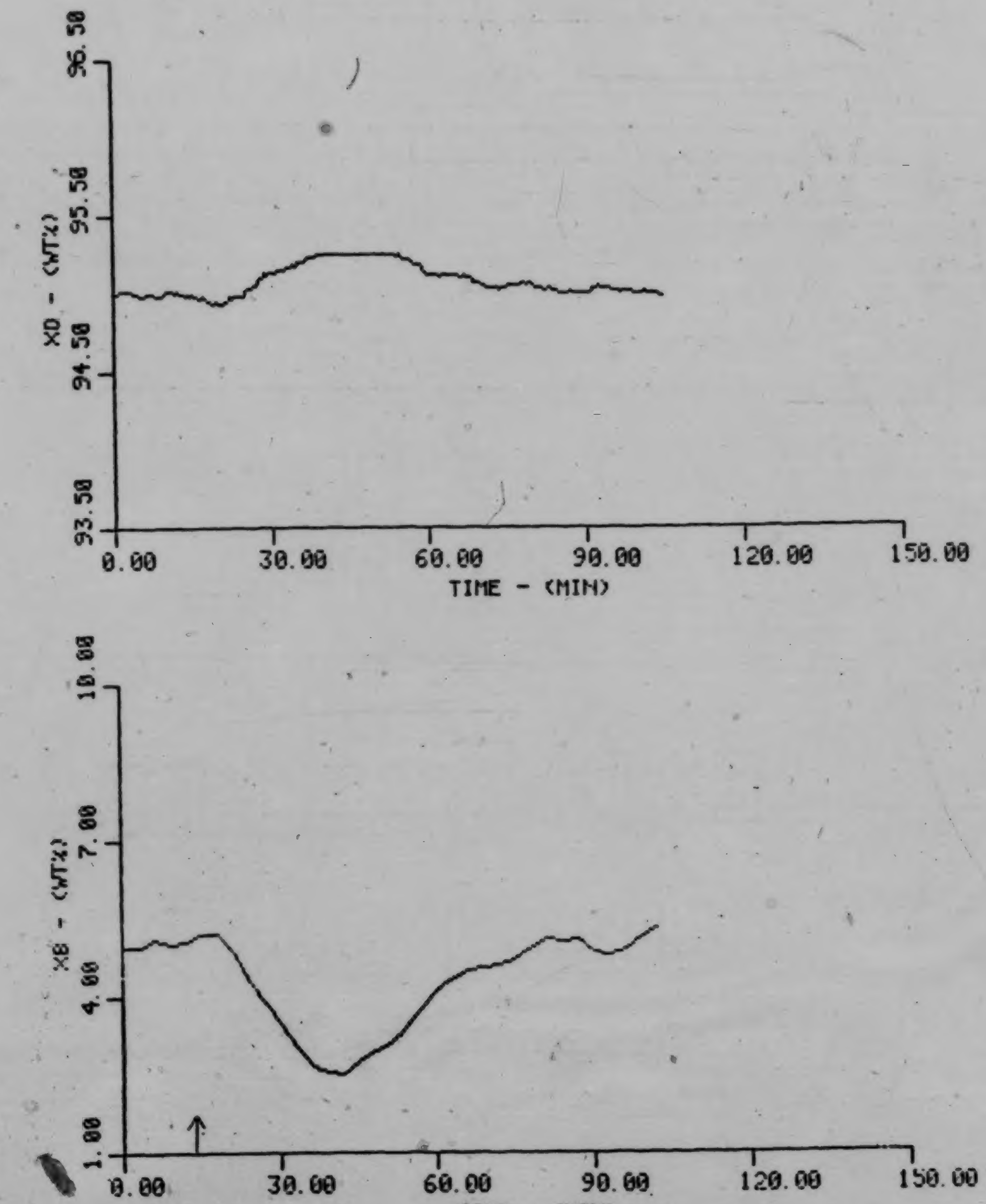

Figure 5.10 Multiloop PID Control of Terminal Compositions for a Step Decrease in Feed Flow Rate to its Normal Steady State Value

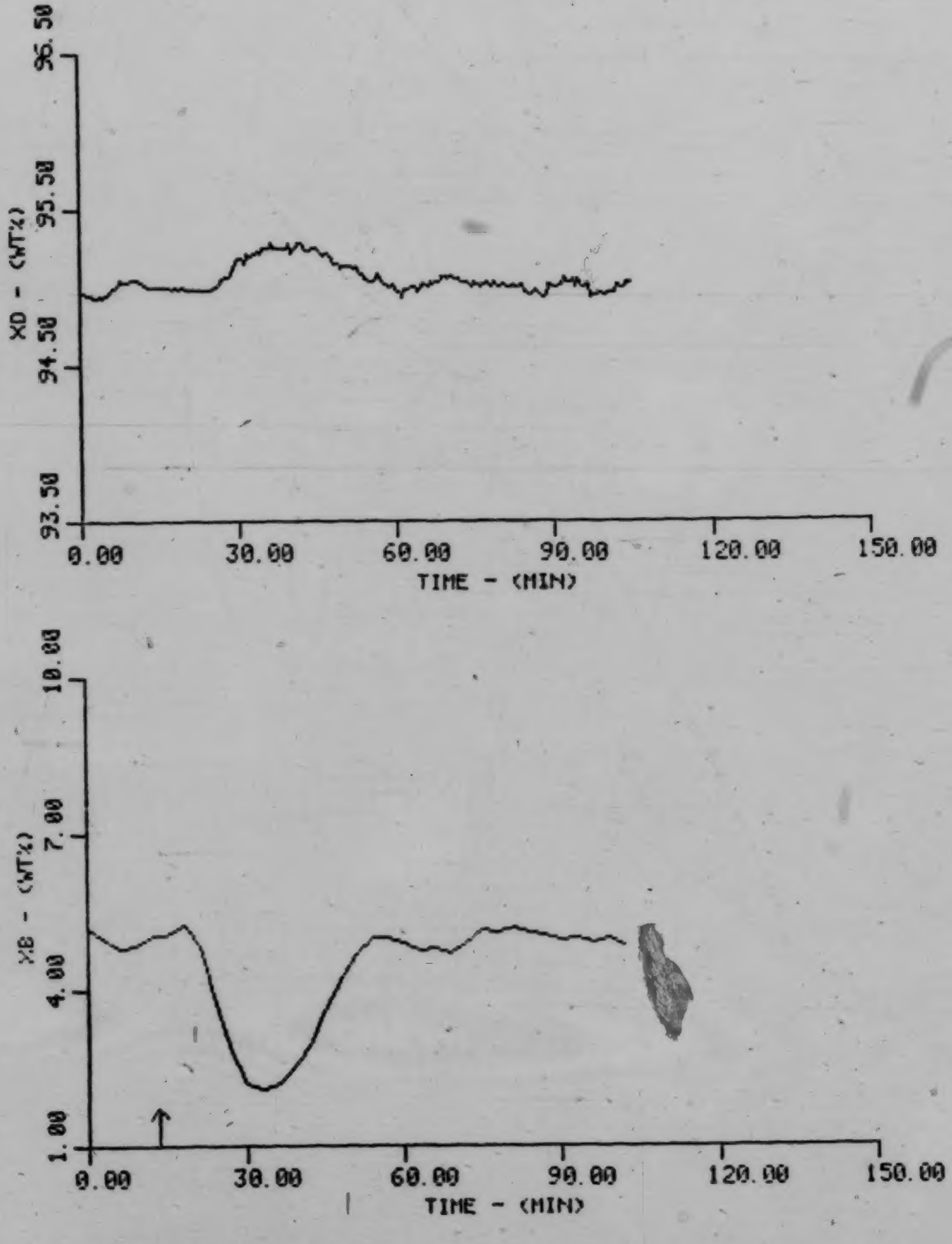

Figure 5.11 Multiloop PID Control of Terminal Compositions for a -25% Step Change in Feed Flow Rate

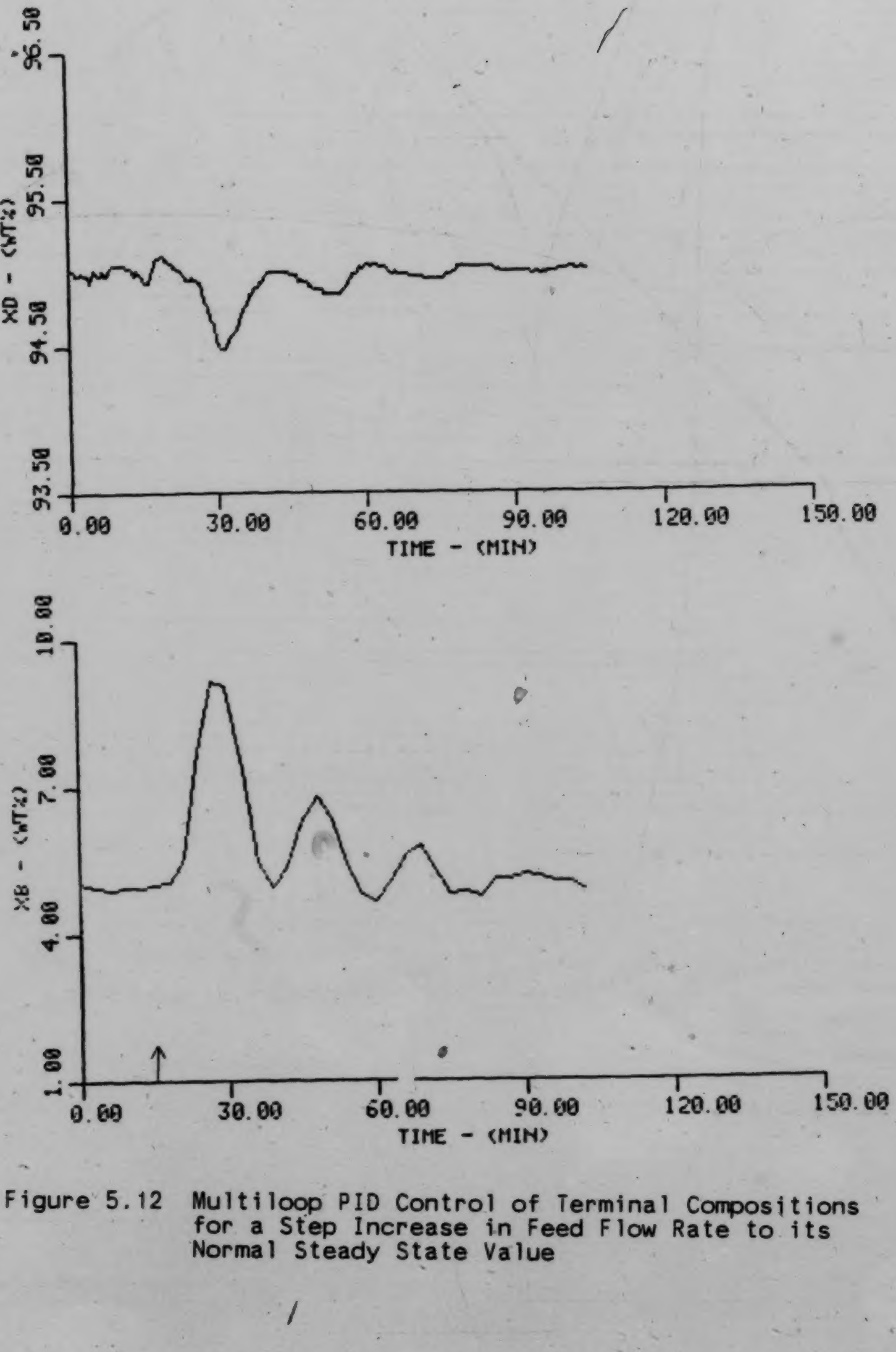

Figure 5.12 Multiloop PID Control of Terminal Compositions for a Step Increase in Feed Flow Rate to its Normal Steady State Value

5.5 TOP COMPOSITION CONTROL

This section contains the experimental responses achieved using the self-tuning controller for overhead composition control. Results are presented to show the effect on control behaviour of:

a. removing Q-weighting (Q-WT);

b. changing sampling time;

c. stopping identification.

Top composition control was selected to demonstrate some characteristic of the self-tuning controller because of the loop's smaller time constant and the allowable user choice of sampling rate for the overhead composition from the continuos measurement signal of the capacitance cell.

5.5.1 Control Performance Using the STC with Q-weighting

The initial controller parameters and options used for self-tuning control when the column was subjected to the different feed disturbances are shown in Table 5.2.

The top composition response when the self-tuning controller is first made operative with zero initial parameter estimates is shown in Figure 5.13. The changes in the parameters during the initial tuning period are shown in Figures 5.14 and 5.15. It can be seen that even starting with zero inital estimates, the parameters have converged after less than 30 sampling intervals. With the parameters having converged, the feed flow rate was decreased by 25%,

Table 5.2 Controller Parameters and Options for STC Top Composition Control

Identification Scheme	Recursive Square Root
G Polynomial	EB
Number of Parameters	NG1 = 3 NF = 2 NH = 1 K1 = 1
Parameter Fixed	$h_0 = -1$
Initial Value of Parameters	All set to zero
Q-weighting	K_p = 3.676 (g/s)/wt% K_i = 0.919 (g/s)/wt%
P-weighting	Set to 1
Sampling Interval	1 minute
Forgetting Factor	0.99
Initial $\underline{\underline{P}}^c$ Matrix	$1000\underline{\underline{I}}$
Incremental Control Limit	2.3 g/s

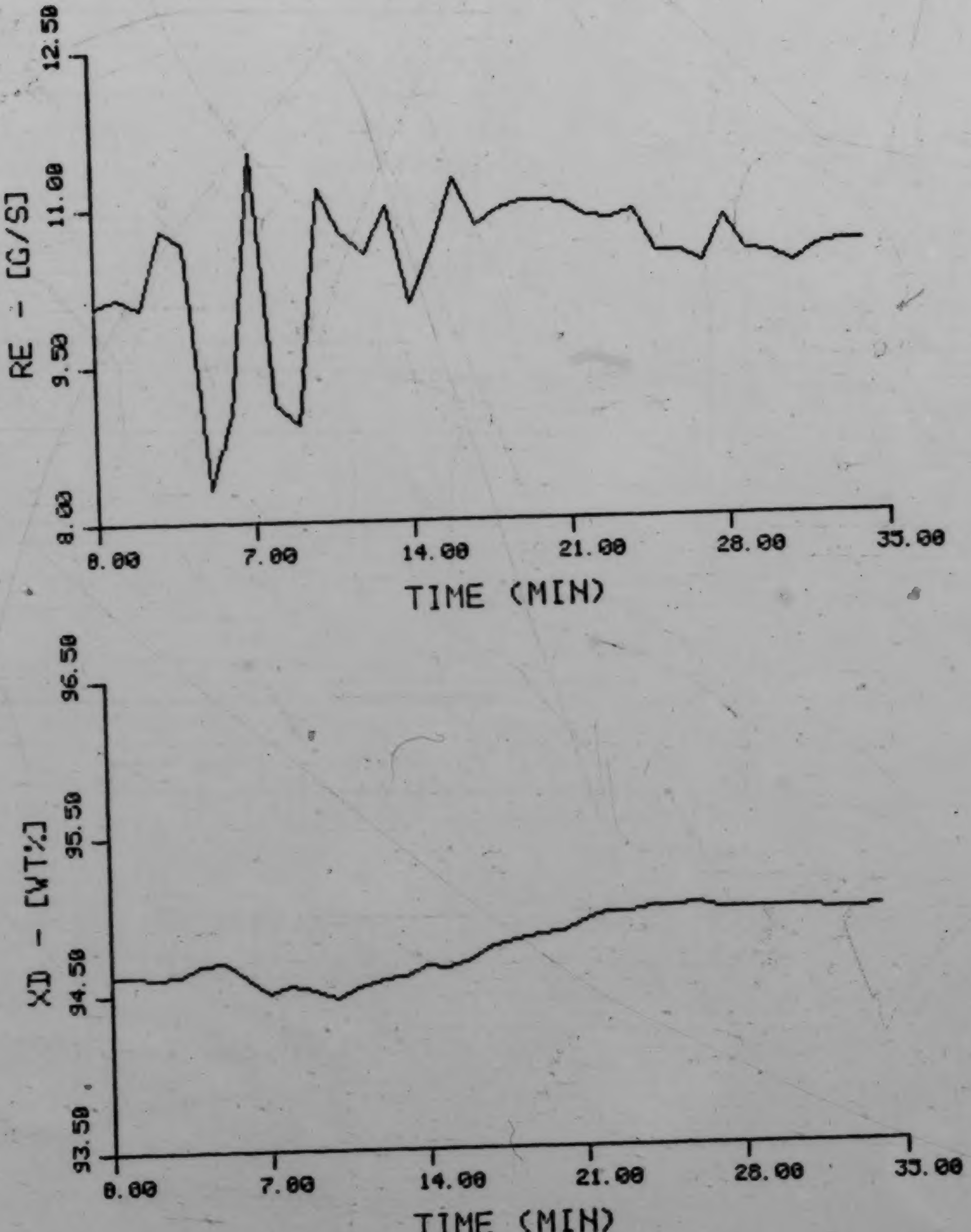

Figure 5.13 Top Composition Behaviour When Operation of the STC With Q-WT is Initiated

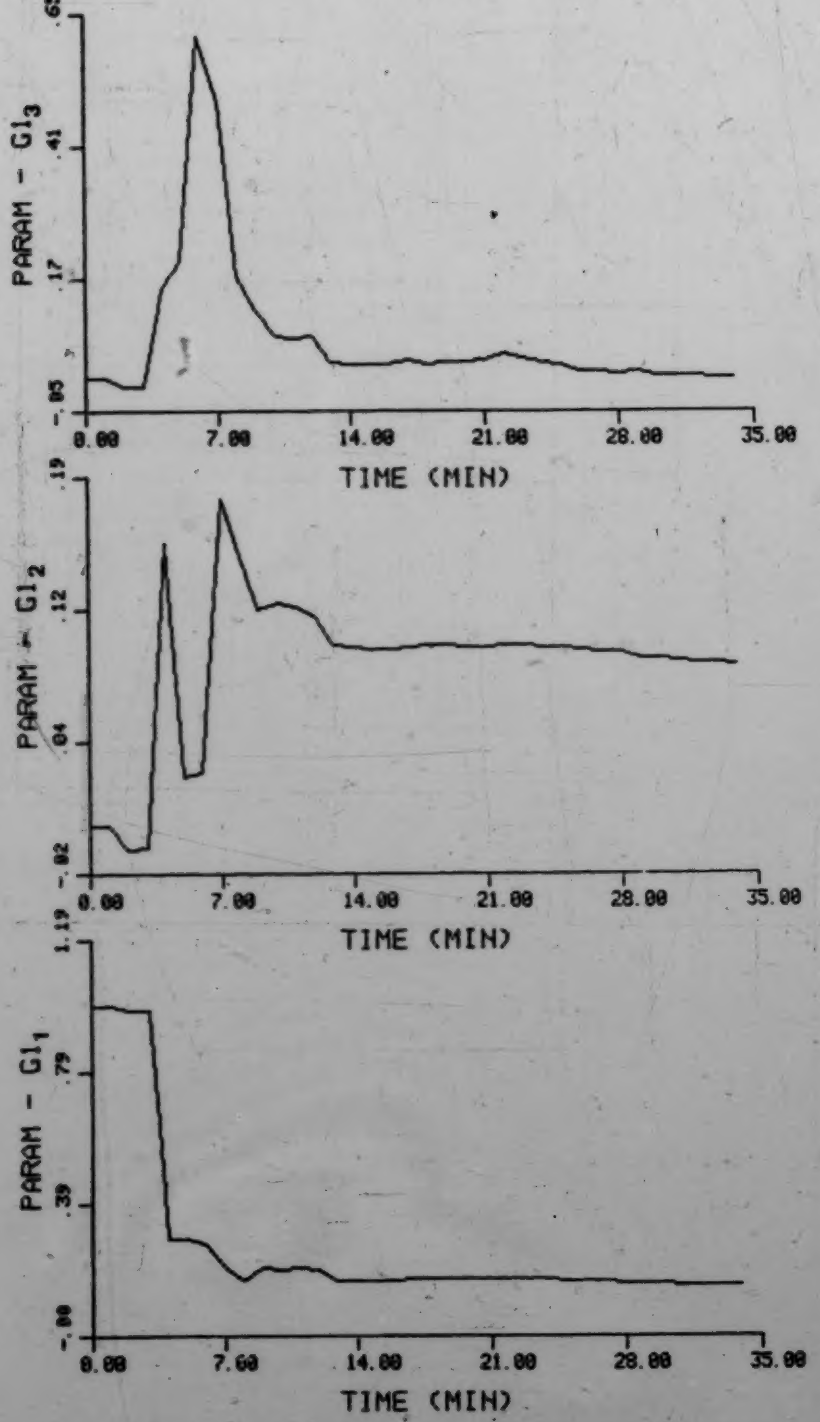

Figure 5.14 Variation of G1 Parameters in the Initial Tuning Period for STC With Q-WT

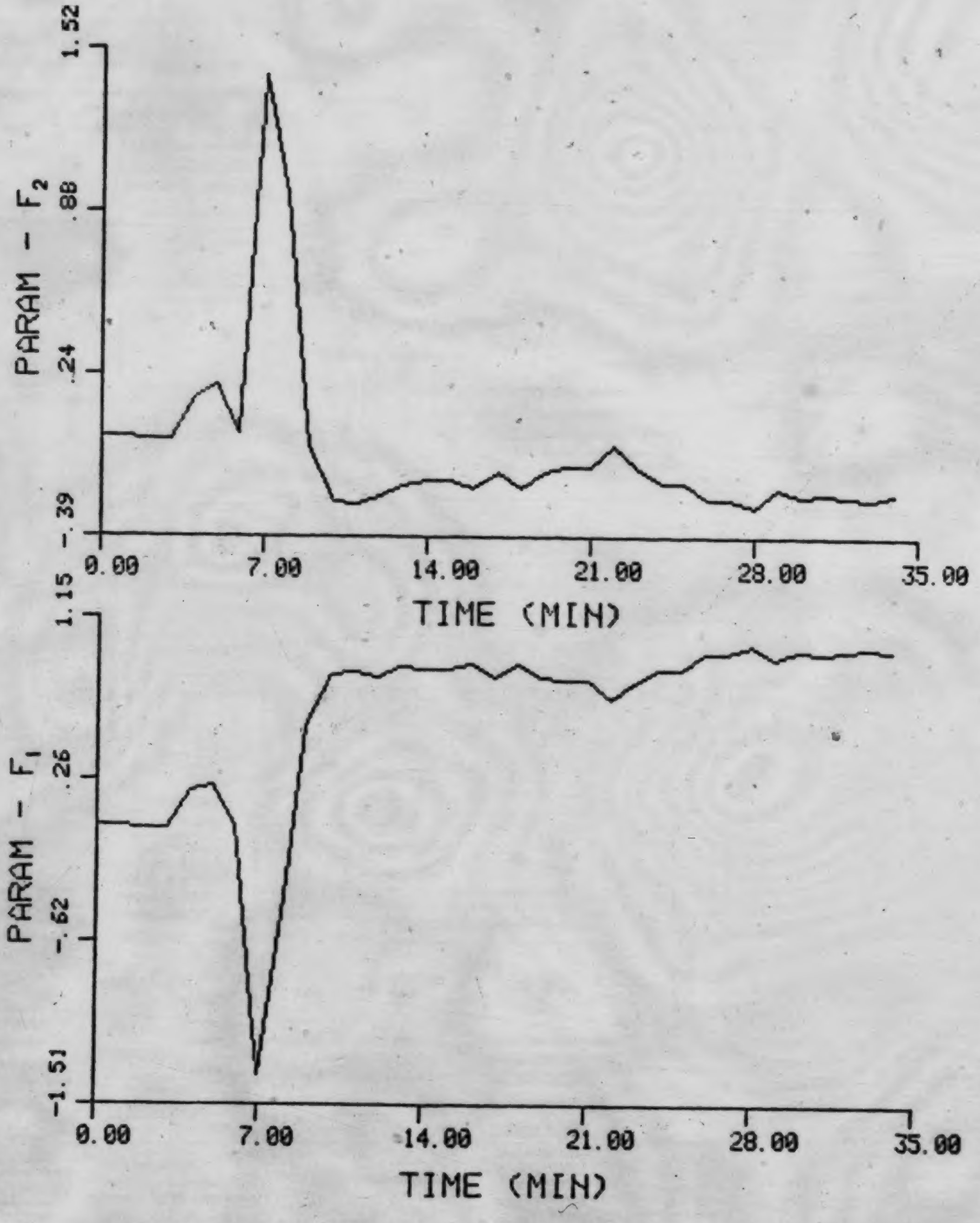

Figure 5.15 Variation of F Parameters in the Initial Tuning Period for STC With Q-WT

the system allowed to reach steady state and the flow increased to its normal steady state rate. The controlled responses for these disturbances are shown in Figures 5.16 and 5.17. To provide a quantitative indication of the controller performance, the absolute error values are calculated for 60 sampling intervals after the disturbance has been introduced. These values are given in Table 5.3. Also shown are the results from duplicate runs.

Table 5.3 Summary of Top Composition Absolute Error Values (Over 60 Samples) for STC with Q-weighting

Run No.	Figure	Type of Disturbance	SAE (wt%)
2-2	5.16	-25% to Feed	2.177
2-3	5.17	Return to S.S.	2.197
5-4	Duplicate	-25% to Feed	2.347
5-5	Duplicate	Return to S.S.	1.867

Comparison of the SAE results with those shown in Table 5.1, shows that the STC performs better than the PID controller for the feed disturbances used. While the SAE achieved by the STC is not much better than the PID case, it should be noted that the PID results were obtained only after considerable time had been expended to tune the controller. This is in marked contrast to the STC results obtained using the first Q-weighting selected (cf. values given in Table 5.2).

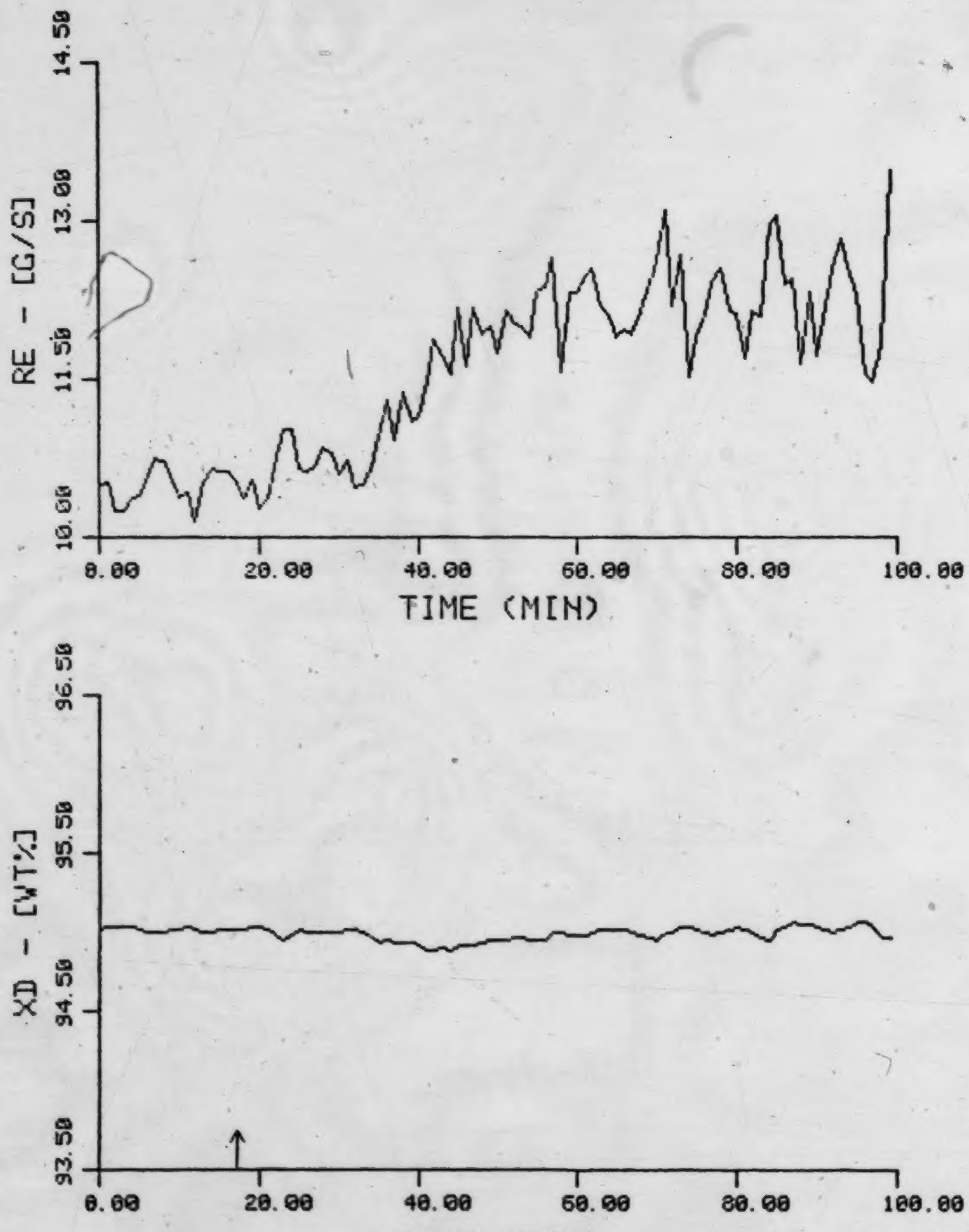

Figure 5.16 ST Control of Top Composition for a -25% Step Decrease in Feed Flow Rate With Q-WT

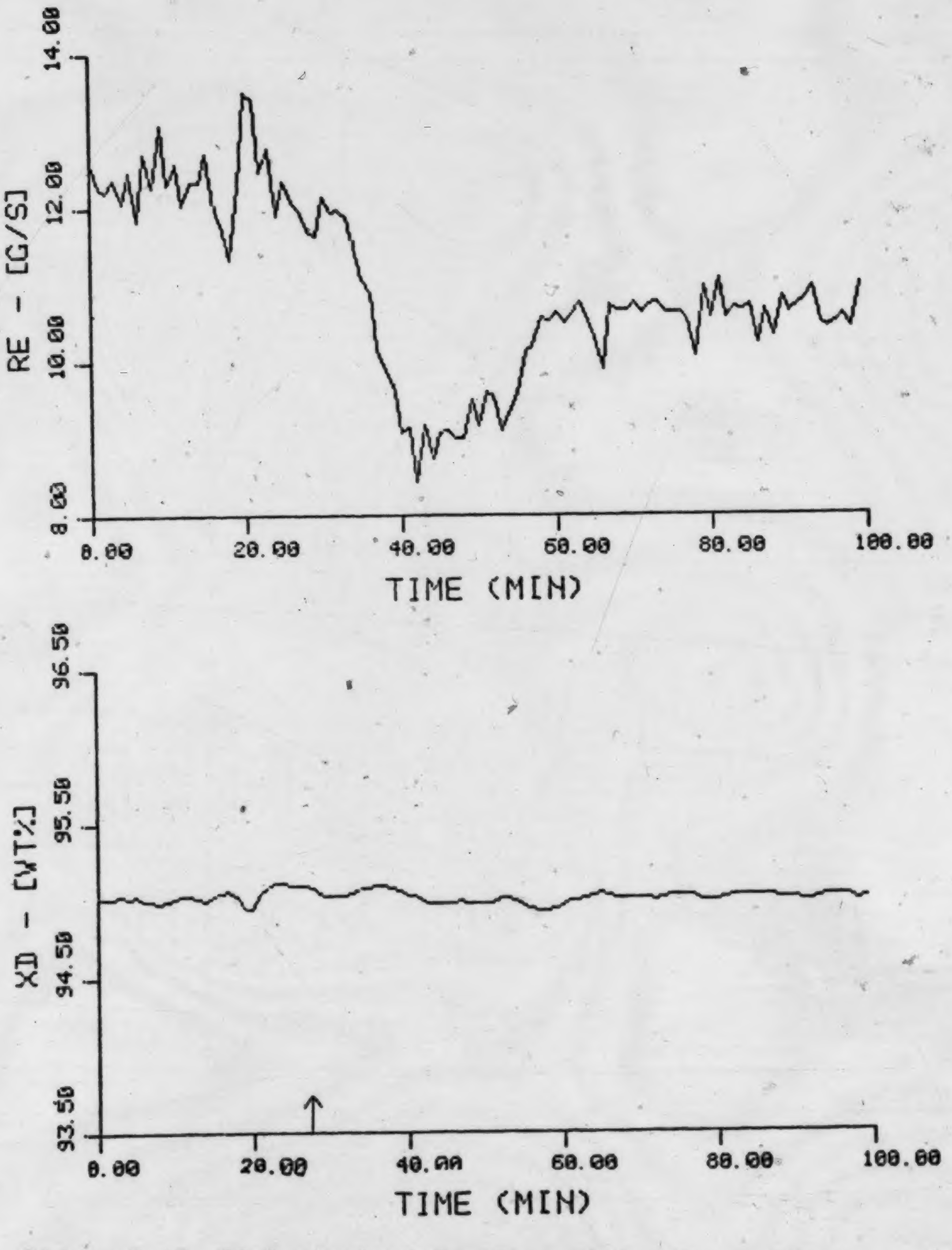

Figure 5.17 ST Control of Top Composition for a Step Increase in Feed Flow Rate to its Normal Steady State Value With Q-WT

5.5.2 Control Performance Using the STC Without Q-weighting

To illustrate the effect of the Q-weighting (Q-WT), the STC was used to control the top composition with the Q-weighting removed. The initial controller parameters and options are the same as those given in Table 5.2 except that the Q-weighting is set to zero. Figure 5.18 shows the top composition response when the controller is first applied while the variation of the parameters as they adapt during the initial identification period is displayed in Figures 5.19 and 5.20. As in the case with the Q-weighting, the parameters have converged after 30 samples. The response of the top composition for a -25% decrease in feed flow and the subsequent change to the normal steady state flow rate are shown in Figures 5.21 and 5.22. The SAE for these results and those of some duplicate runs are compared with the previous results obtained using Q-weighting in Table 5.4.

Table 5.4 Comparison of Top Composition Absolute Error Values (Over 60 Samples) for STC With and Without Q-weighting

	With Q-weighting		Without Q-weighting	
Type of Disturbance	Figure	SAE (wt%)	Figure	SAE (wt%)
-25% to Feed	5.16	2.177	5.21	4.278
Return to S.S.	5.17	2.197	5.22	2.693
-25% to Feed	Duplicate	2.347	Duplicate	2.906
Return to S.S.	Duplicate	1.867	Duplicate	3.327

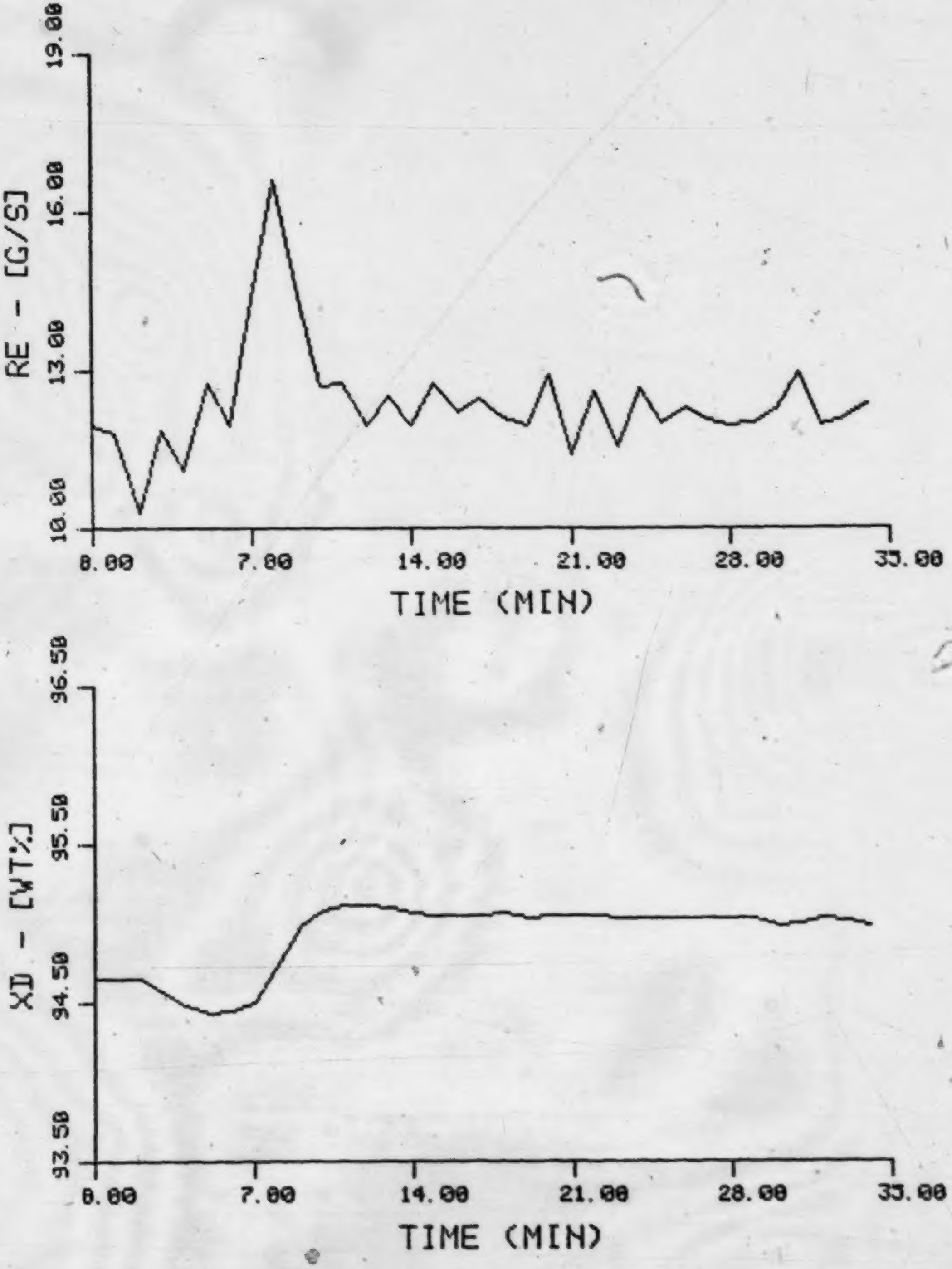

Figure 5.18 Top Composition Behaviour When Operation of the STC Without Q-WT is Initiated

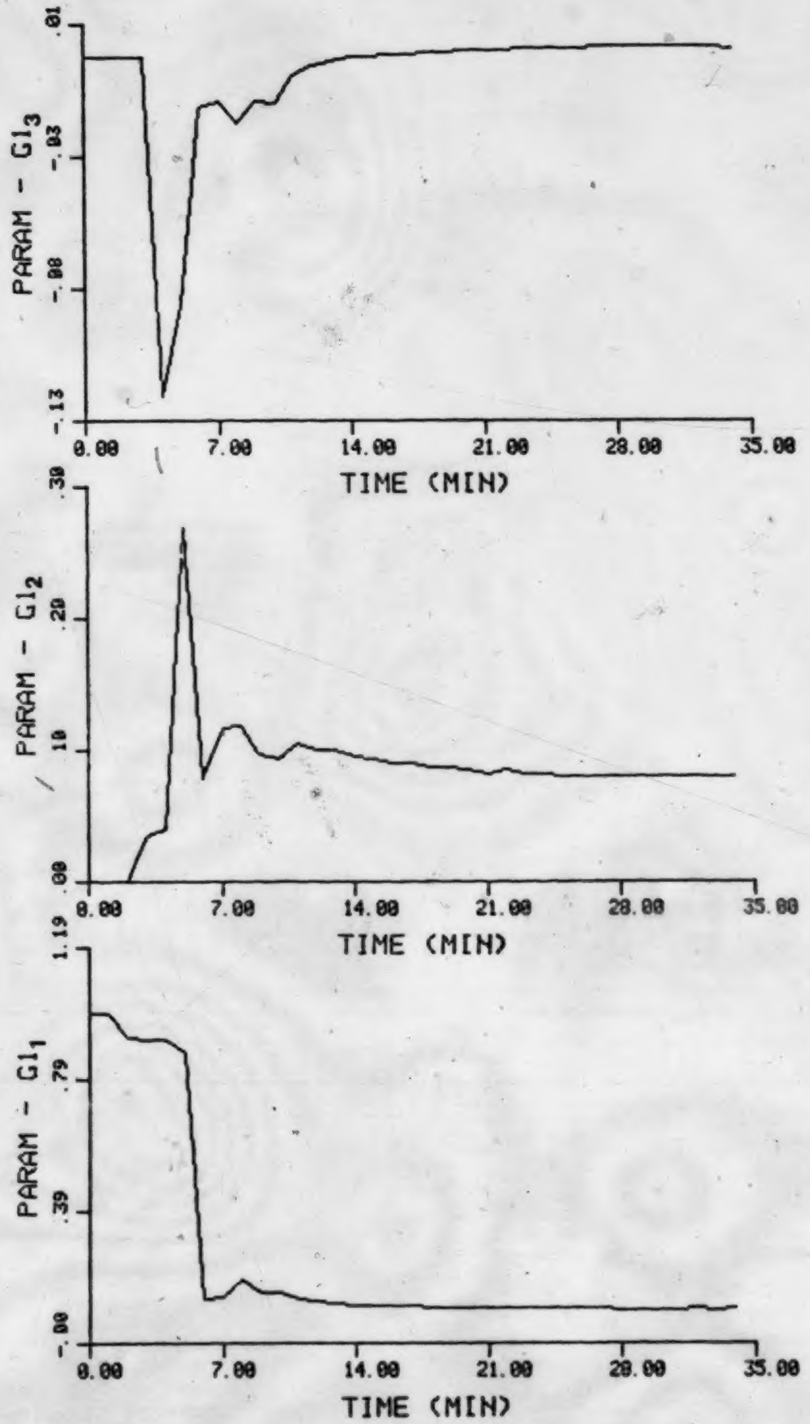

Figure 5.19 Variation of G1 Parameters in the Initial Tuning Period for STC Without Q-WT

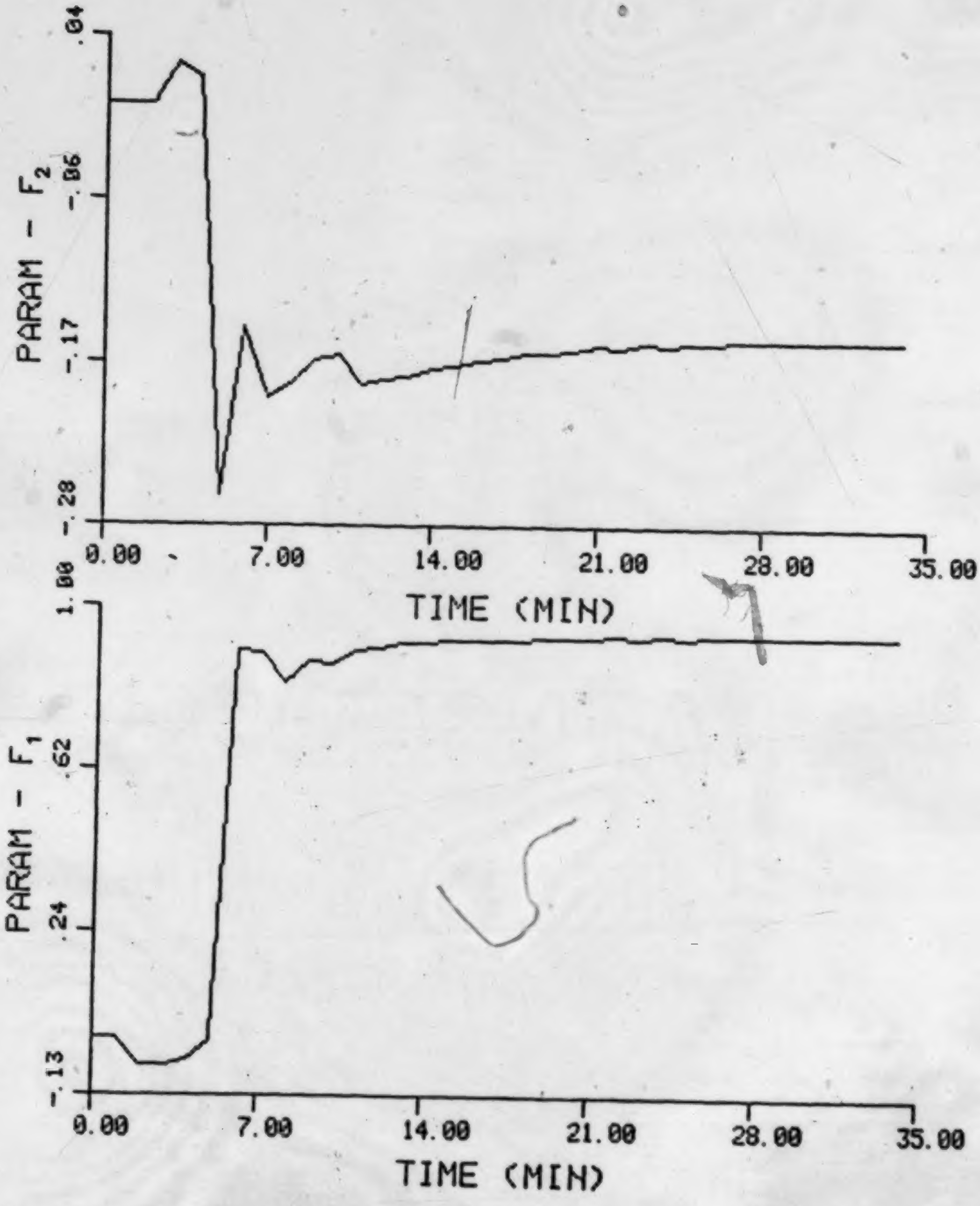

Figure 5.20 Variation of F Parameters in the Initial Tuning Period for STC Without Q-WT

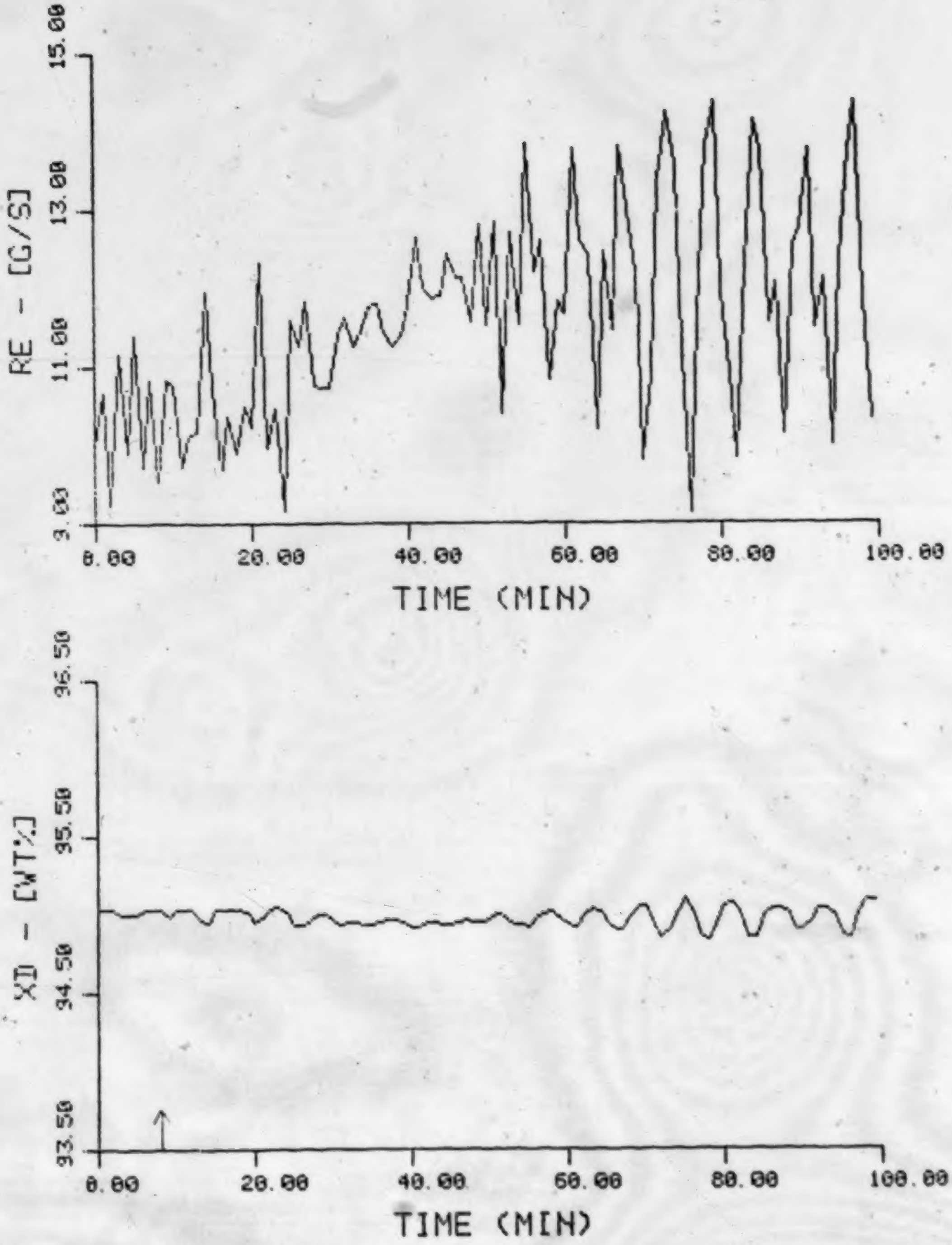

Figure 5.21 ST Control of Top Composition for a -25% Step Decrease in Feed Flow Rate Without Q-WT

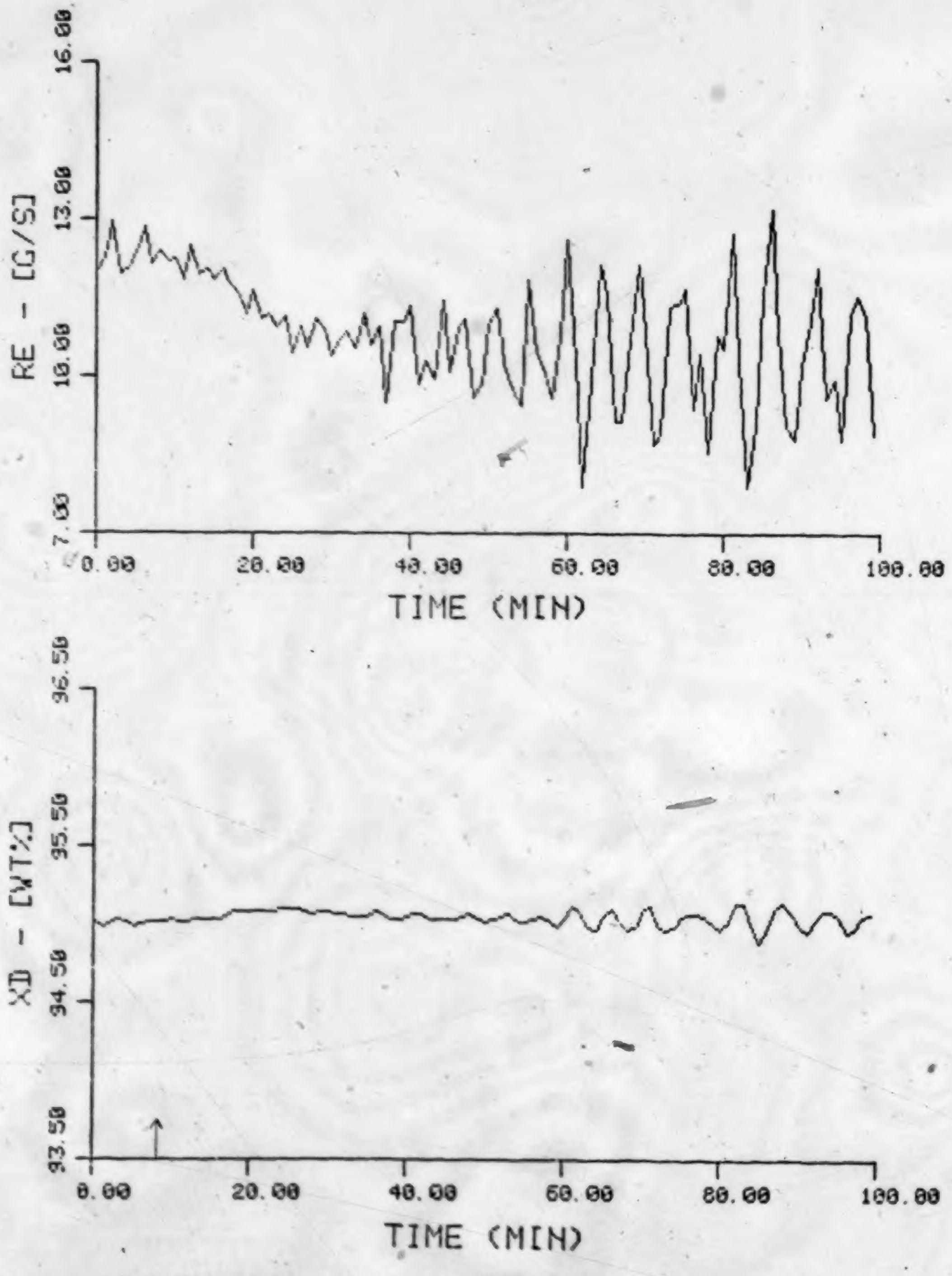

Figure 5.22 ST Control of Top Composition for a Step Increase in Feed Flow Rate to its Normal Steady State Value Without Q-WT

As discussed in Chapter Two, the Q-weighting adds a penalty for control effort so removing the Q-weighting allows the manipulated variable to exhibit larger deviations. Comparison of the variations in reflux flow rate shown in Figure 5.21 and 5.16 shows that this is indeed the case. It can be seen that without Q-weighting, the magnitude of the reflux flow variation is twice the variation that resulted when Q-weighting was used. The larger variation in reflux flow due to the removal of the Q-weighting causes the control performance to deteriorate as shown by the SAE values for STC with and without Q-weighting given in Table 5.4.

Comparing the initial tuning in period for the cases with and without Q-weighting, it is seen that the added penalty in control effort helps to reduce the variation in reflux flow. In addition, without the Q-weighting, the controller demands a maximum reflux flow of over 16 g/s but using the Q-weighting, the maximum is reduced to 11.5 g/s. This reduction in the maximum control output leads to less overshoot in the overhead composition response.

These results clearly show that the use of the Q-weighting reduces the amount of variation in the reflux flow rate. This will lead to an improvement in the controller performance in terms of the SAE criteria. Futhermore, the use of Q-weighting does not slow down the rate at which the parameters converge during the initial tuning in period and it gives the added advantage of reducing the maximum reflux flow required during the initial transition period.

5.5.3 Effect of Sampling Time

To show the effect of sampling time, experimental runs were made using times of two and three minutes. The experimental responses for a -25% step decrease in feed flow rate, for the two and three minute rates are shown in Figures 5.23 and 5.24. With the exception of the change in sampling time and the absence of the Q-weighting, the initial controller parameters and options are the same as those shown in Table 5.2. No Q-weighting was employed in order to demonstrate that increasing the sampling time has the same effect as adding the Q-weighting; that is in terms of reducing the oscillation in the manipulated variable[24].

Comparing the overhead composition response for the different sampling times, it is seen that by increasing the time to two minutes, the magnitude of the variation in the reflux flow is greatly reduced. As can be seen from the absolute error values in Table 5.5, the performance is not much better than that achieved using the one minute sampling rate because at the two minute sampling time, the controller responds more slowly to an unknown disturbance since the controller is only acting in the feedback mode. By further increasing the sampling time to three minutes, the magnitude of the oscillation in the reflux flow starts to increase. The controlled response to the disturbance is not as

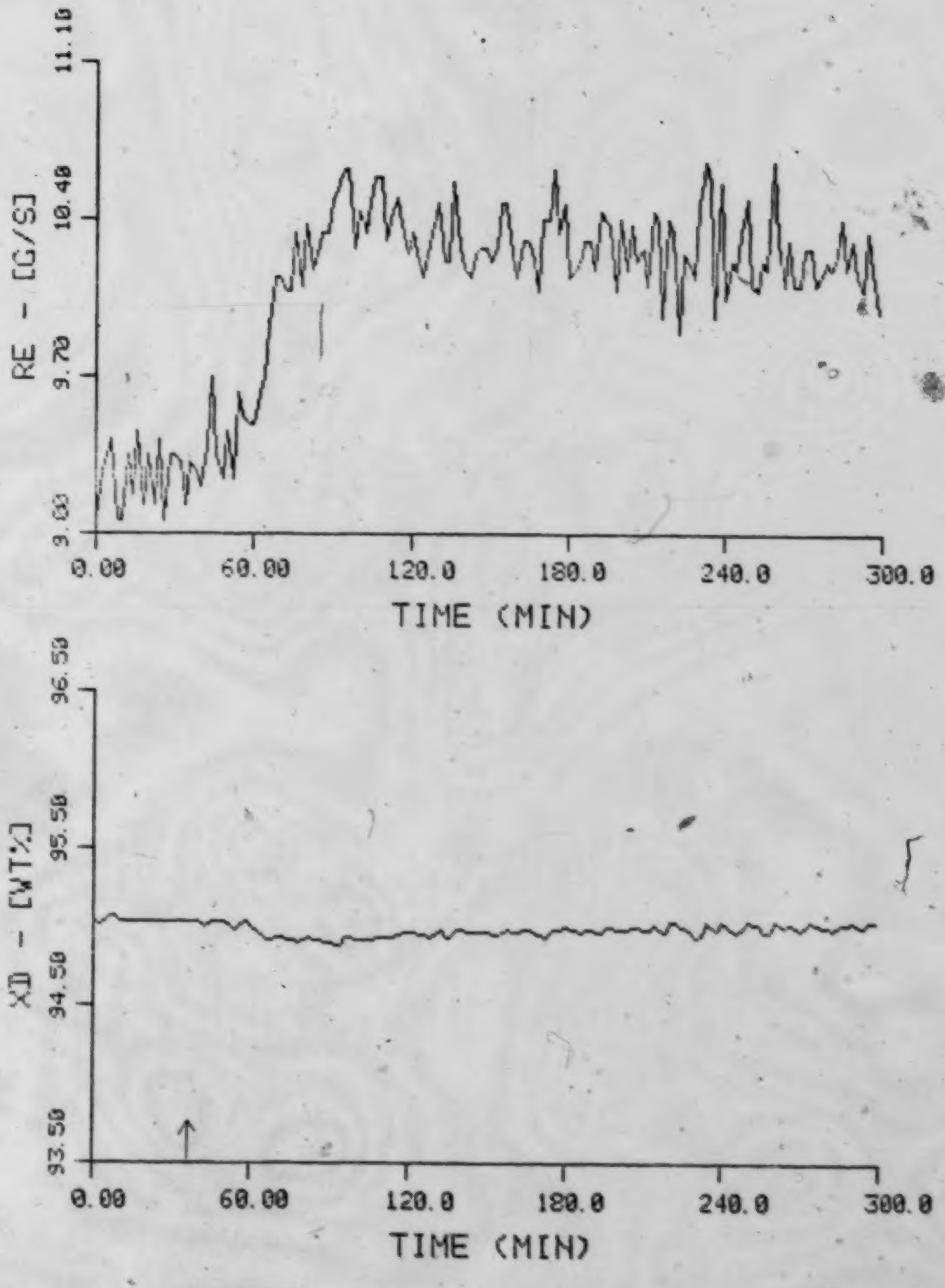

Figure 5.23 ST Control of Top Composition to a -25% Step Decrease in Feed Flow Rate Without Q-Wt: Two Minute Sampling Time

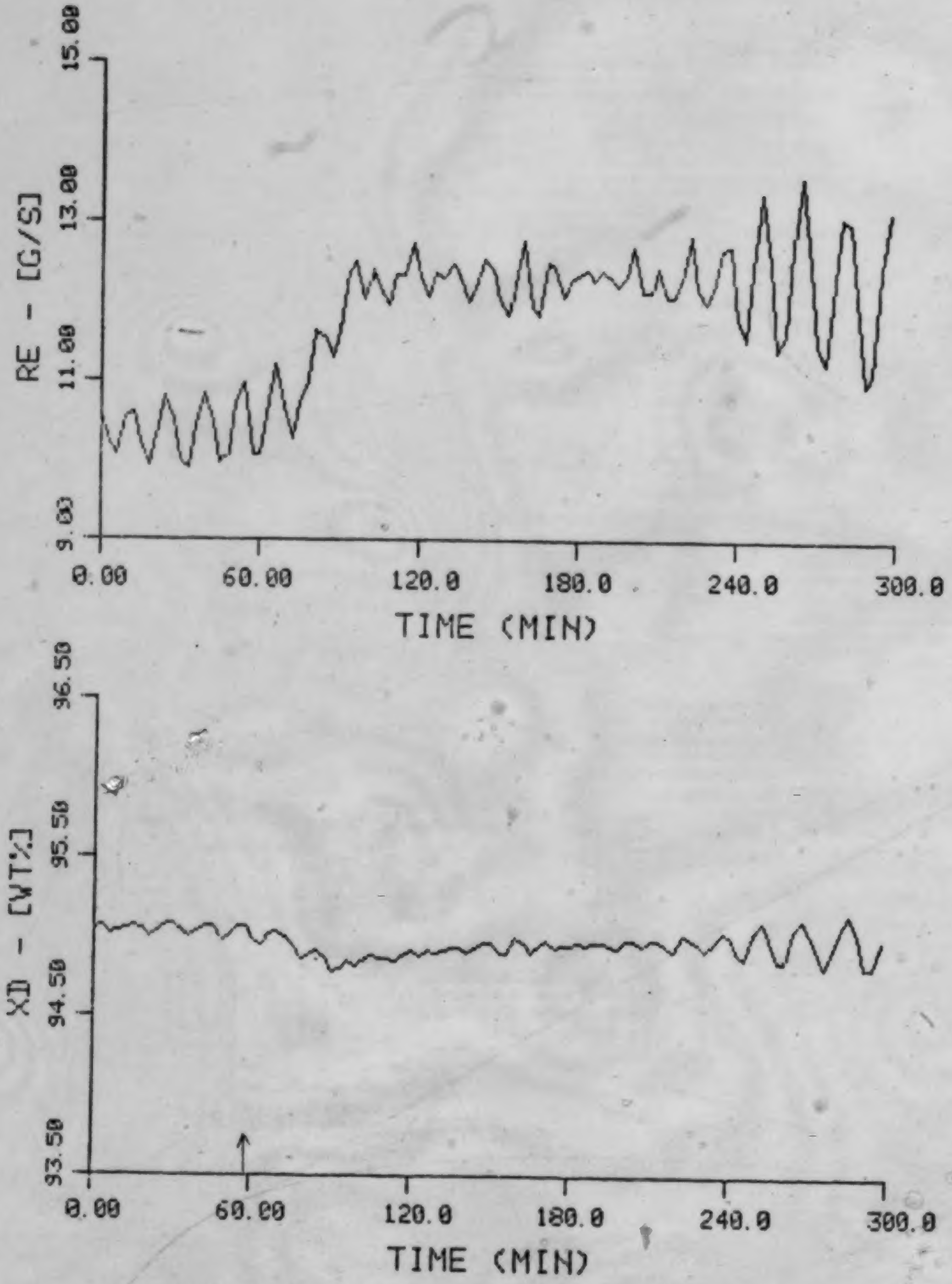

Figure 5.24 ST Control of Top Composition to a -25% Step Decrease in Feed Flow Rate Without Q-Wt: Three Minute Sampling Time

satisfactory because of the larger sampling time.

Table 5.5 Comparison of Top Composition Absolute Error Values Calculated for a Period of One Hour After the Feed Disturbance for Different Sampling Times

Figure	Sampling Time (minutes)	SAE (wt%)
5.16	1	4.278
5.23	2	3.627
5.24	3	6.700

The results show that while it is possible to use larger sampling times to reduce the variation in the reflux flow, the larger sampling time tends to slow down the controller response for a disturbance that has to be detected by feedback of the output variable. For a feedback strategy, it would be better to sample faster and increase the weighting placed on the control effort. However, for a controller with feedforward action, it should be possible to achieve the same control performance with a larger sampling time.

5.5.4 Effect on Control Performance when Identification is Stopped

From Equation (2.34), the control law can be expressed as:

$$F\bar{y}_{t+k} + Gu_t - HQu_t + H\bar{w}_t + D\bar{v}_t = 0 \tag{5.1}$$

and without feedforward action, the control law reduces to:

$$F\bar{y}_{t+k} + Gu_t - HQu_t + H\bar{w}_t = 0 \qquad (5.2)$$

At steady state, the outputs and inputs remain constant and Qu_t tends to zero (cf. Chapter 2). Equation (5.2) becomes:

$$\Sigma F_i\bar{y}_{t+k} + \Sigma G_i u_t - \Sigma H_i\bar{w}_t = 0 \qquad (5.3)$$

If the identification scheme is stopped, the sum of the coefficients for each of the polynomials becomes constant. When a disturbance is introduced, it is clear that the control output will reach a new steady state value. Since the sum of these coefficents remains the same, to satisfy Equation (5.3), only the process output value can change hence resulting in an offset. The magnitude of the offset will depend on the G and F parameters. If the sum of the G parameters is small compared to the sum of the F parameters, only a small change in $\bar{y}_{t+k}$ is needed, so a smaller offset occurs.

To demonstrate the effect discussed, a run was made where the identification was stopped after the STC had brought the top composition to its steady state value. The initial controller parameters and options are the same as those given in Table 5.2 with the exception that Q-weighting is not used. The response of the top composition to a -25% step change from the steady state feed flow rate is recorded in Figure 5.25. Although the offset is small, it is clear that there is an offset of about 0.05%. By resuming the

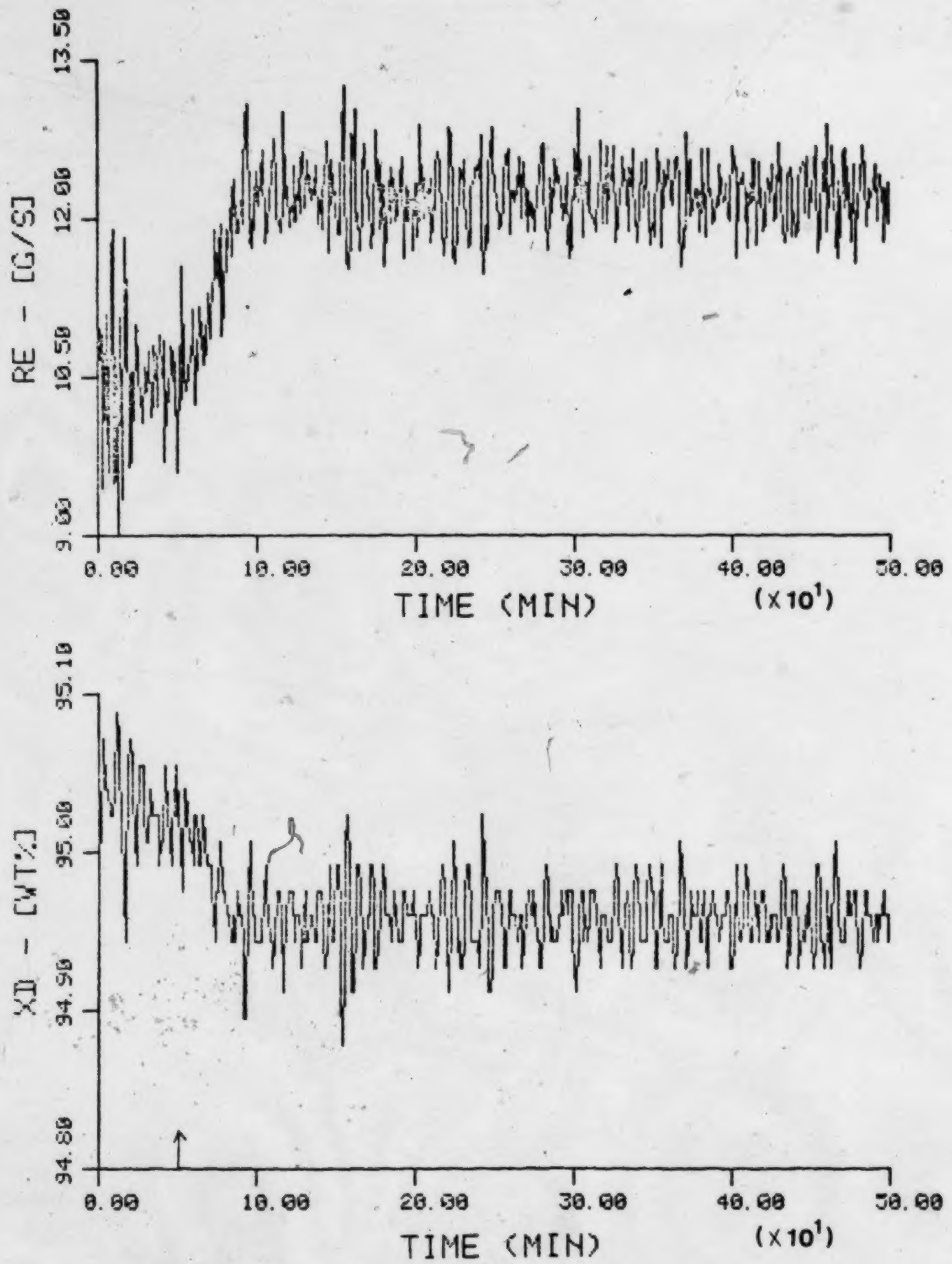

Figure 5.25 ST Control of Top Composition to a -25% Step Change in Feed Flow Rate Without Q-WT and the Identification Stopped

indentification, the parameters will readjust to remove the offset as can be seen from the response shown in Figure 5.26.

5.6 BOTTOM COMPOSITION CONTROL WITH STC

The self-tuning controller was used to control the bottom composition, despite changes in feed flow rate, by manipulating the steam flow rate. The reflux flow was fixed at its normal steady state value of 10.2 g/s. The initial self-tuning controller parameters and options are given in Table 5.6. The control behavior for bottom composition that resulted for the four different feed flow rate disturbances used in this study are shown in Figures 5.27 to 5.30. The results given are for STC runs that already have 'good' parameter estimates. Some re-tuning of the Q-weighting was necessary with the resulting values as noted. Table 5.7 gives a summary of the absolute error values for bottom composition control for a period of 1 1/2 hour after the feed rate was changed for both the STC and the previous PID results (cf. Table 5.1). It can be seen from these values that the STC performs better than PID for the +25% increase in feed flow rate away from the steady state value and for the decrease back to steady state feed flow, while PID is better than the STC for the other two disturbances. On the basis of these results, it can be seen that both controllers performed equally well. However, it should be noted that considerable more time was needed to tune the PID

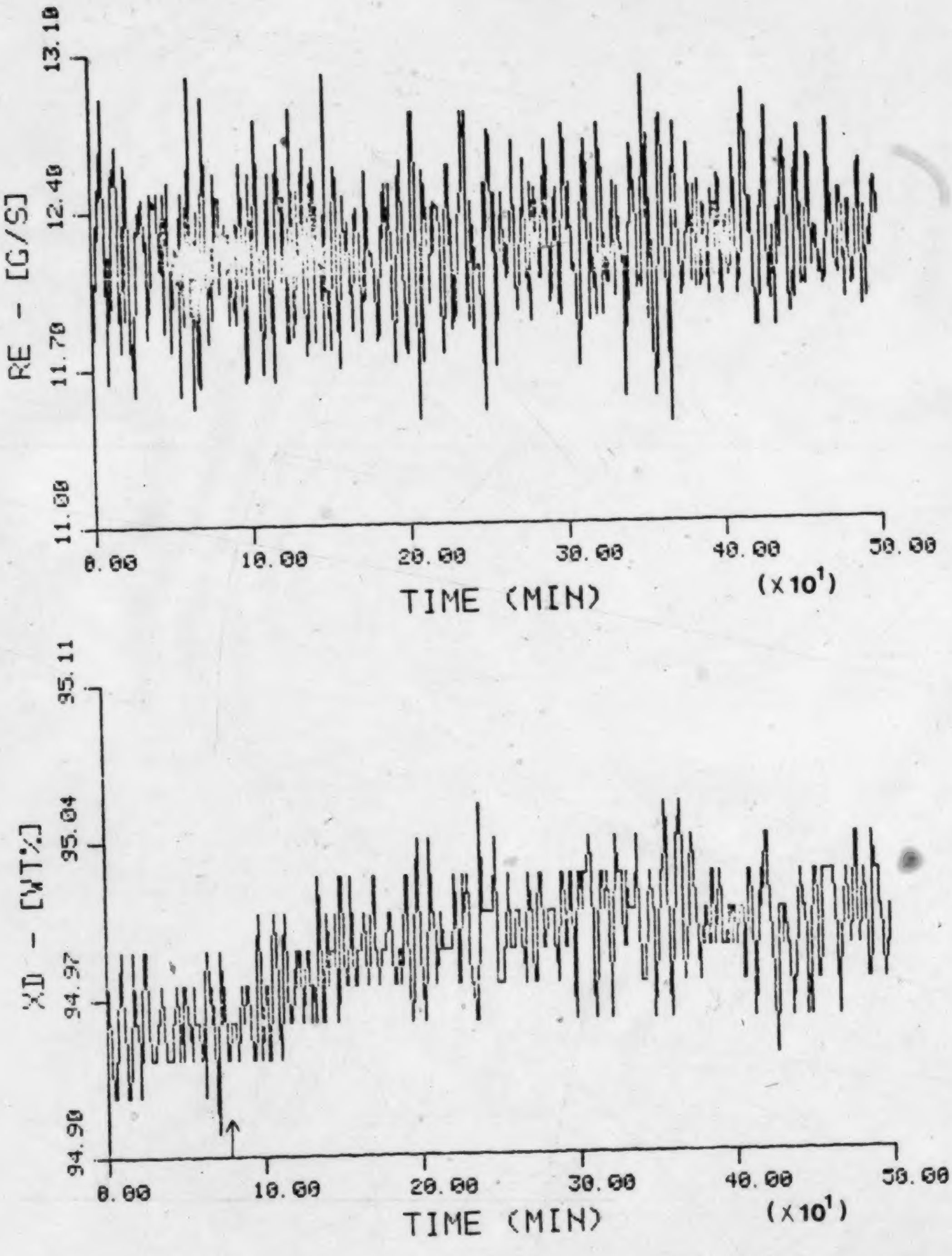

Figure 5.26 Top Composition Response After Resuming Identification in the STC

Table 5.6 Controller Parameters and Options for STC Bottom Composition Control

Identification Scheme	Recursive Square Root
G Polynomial	EB
Number of Parameters	NG1 = 4 NF = 3 ND = 5 (FF added) NH = 1 K1 = 1 K3 = 1 (FF added)
Parameter Fixed	$h_o = -1$
Initial Value of Parameters	All set to zero
Q-weighting	$k_p = 1.145$ (g/s)/wt% $k_i = 0.226$ (g/s)/wt%
P-weighting	Set to 1
Sampling Interval	3 minute
Forgetting Factor	0.99
Initial $\underline{\underline{P}}^c$ Matrix	$1000\underline{\underline{I}}$
Incremental Control Limit	2.25 g/s

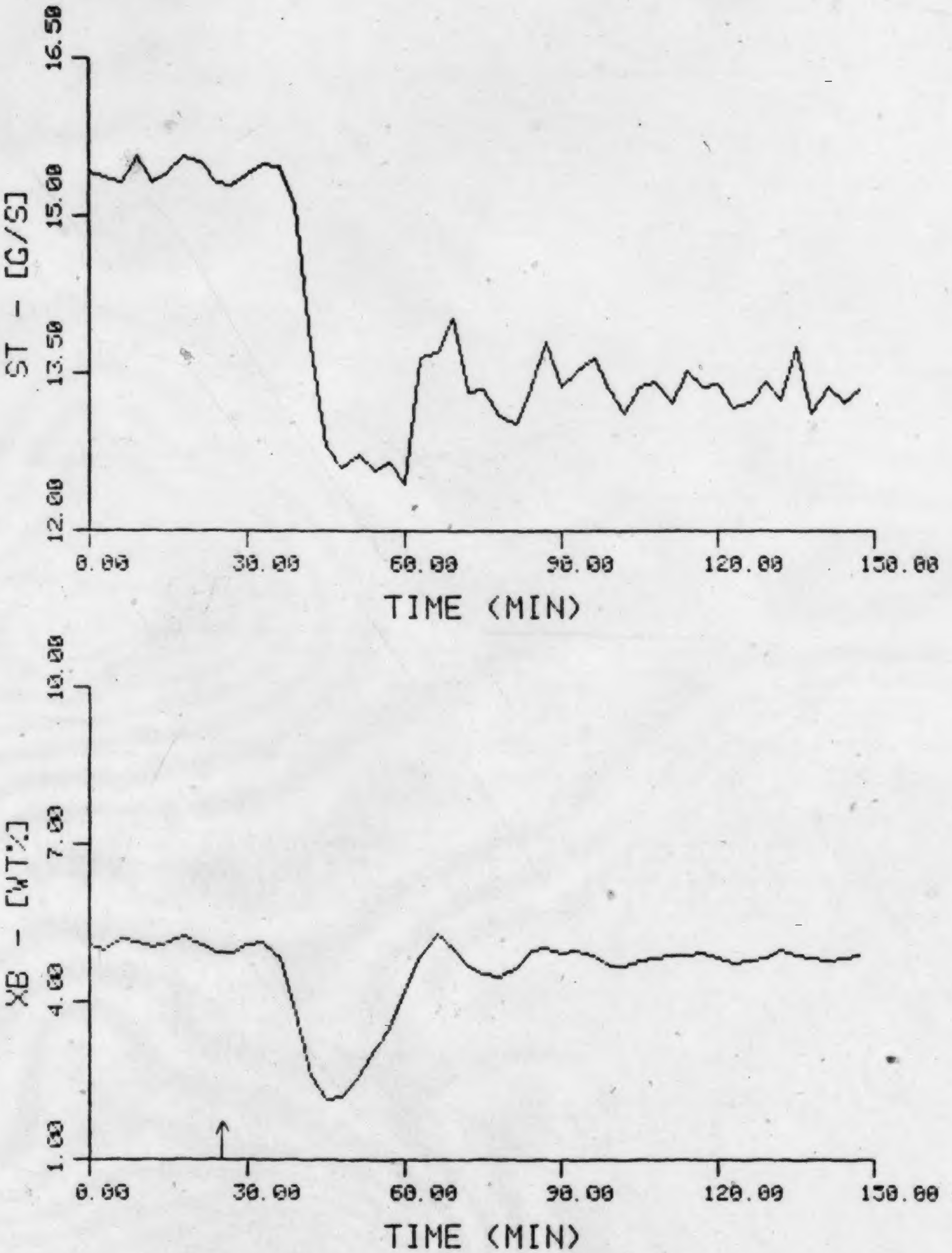

Figure 5.27 ST Control of Bottom Composition for a -25% Step Change in Feed Flow Rate With Q-WT (k_p - 1.15 and k_i - 0.23)

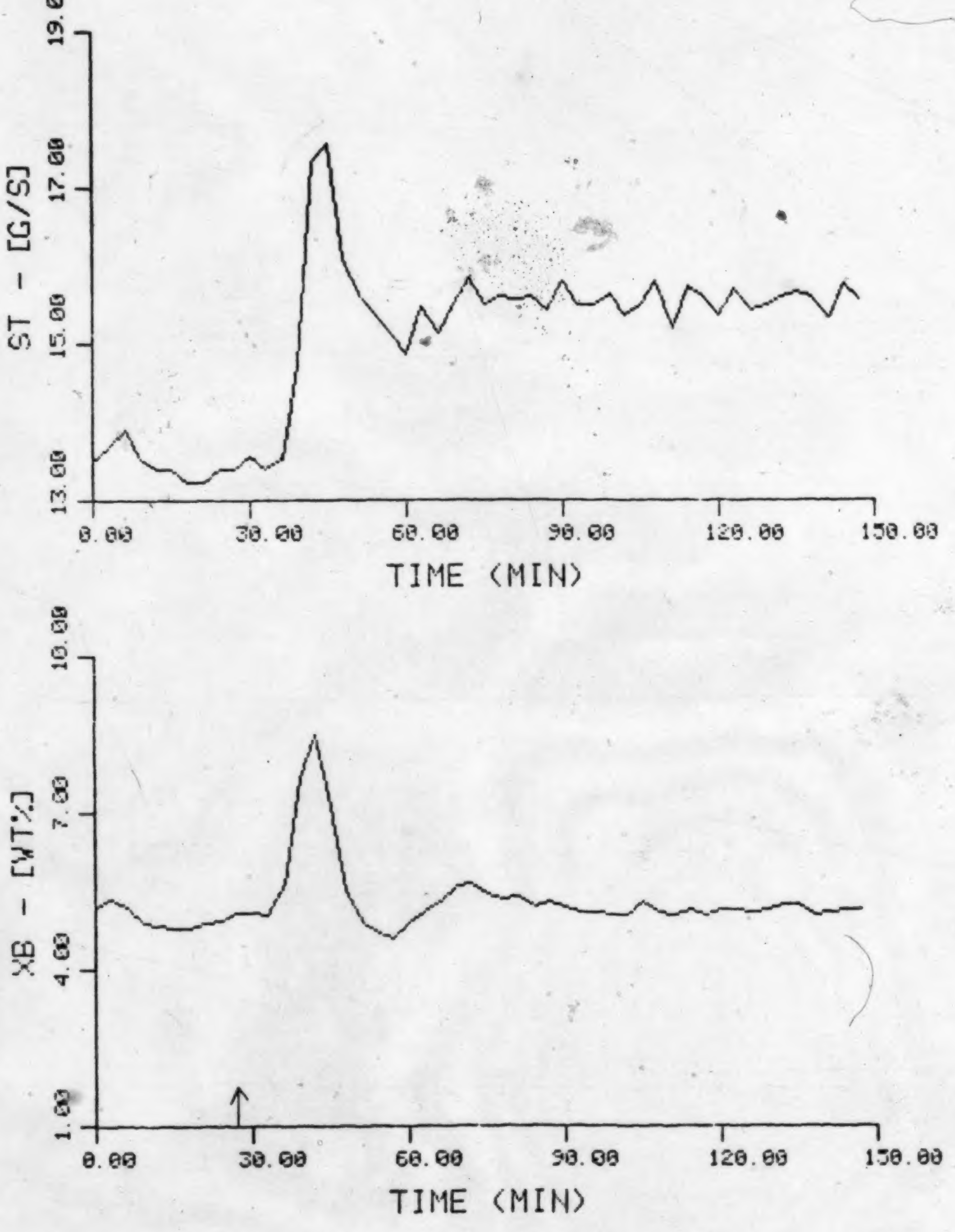

Figure 5.28 ST Control of Bottom Composition for a Step Increase in Feed Flow Rate to its Normal Steady State Value With Q-WT (k_p - 0.90 and k_i - 0.47)

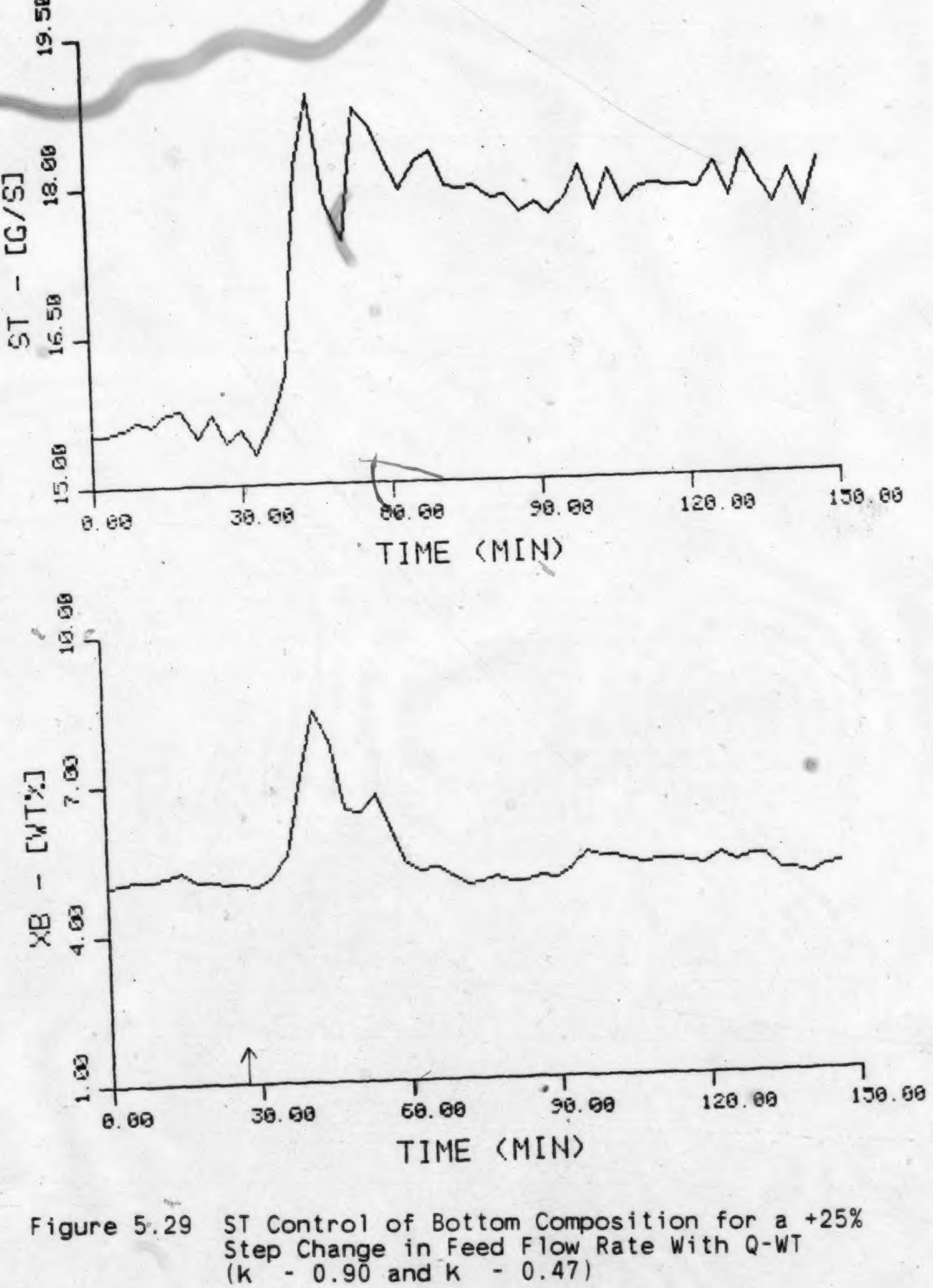

Figure 5.29 ST Control of Bottom Composition for a +25% Step Change in Feed Flow Rate With Q-WT (k - 0.90 and k - 0.47)

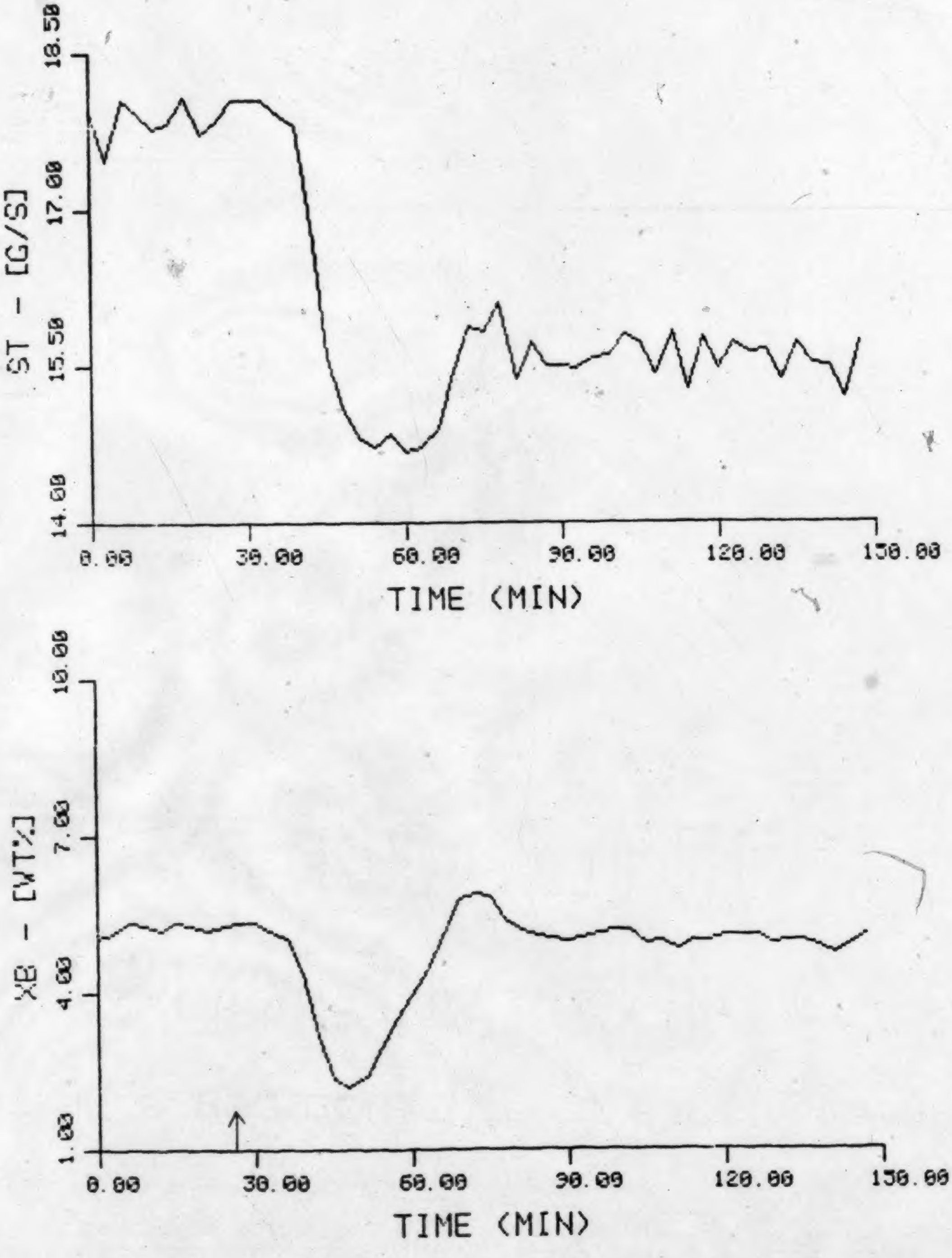

Figure 5.30 ST Control of Bottom Composition for a Step Decrease in Feed Flow Rate to its Normal Steady State Value With Q-WT (k_p - 0.90 and k_i - 0.47)

compensator than the Q-weighting constants. Also, the final Q-weighting parameters are closer to the original estimates. In addition, the PID constants for the different disturbances differ by a considerable amount in comparison to the variations in the Q-weighting parameters for the different disturbances. This can be seen by comparing the difference in the two sets of PID constants for bottom composition control given in Table 5.1 with the difference in the Q-weighting parameters for the responses shown in Figure 5.27 to 5.30. This is because the STC is able to adapt to the nonlinear dynamic behavior of the column.

Table 5.7 Comparison of Bottom Composition Absolute Error Values (over 1 1/2 hour) for PID and STC

	PID Control		ST Control	
Type of Disturbance	Figure	SAE (wt%)	Figure	SAE (wt%)
-25% to Feed	5.7	18.43	5.27	19.70
Return to S.S.	5.8	14.00	5.28	14.90
+25% to Feed	5.5	20.72	5.29	18.76
Return to S.S.	5.6	26.04	5.30	20.51

Additional evidence that the STC handles nonlinearity better than the PID compensator is seen by comparing the performances of the two controllers for the +25% step increase in feed flow and the subsequent step decrease to the normal feed rate (cf. Figures 5.6-5.7 and 5.29-5.30). From the SAE values given in Table 5.7, it can be seen that the STC, compared to the PID compensator, provided similar control performance for theses different step changes in feed flow.

The effect of the addition of feedforward (FF) control action to the STC was studied using the same controller parameters and options given in Table 5.6 except that the values of the G1 and F parameters are initially set equal to the final values obtained when using the STC without feedforward action.

The bottom composition responses for the same four different feed flow rate disturbances are given in Figures 5.31 to 5.34 with the absolute error values for these responses and those of the previous PID and STC tests summarized in Table 5.8.

Table 5.8 Comparison of Bottom Composition Absolute Error Values (over 1 1/2 hour) for PID, STC and STC+FF

	PID Control		ST Control		STC + FF	
Type of Disturbance	Figure	SAE (wt%)	Figure	SAE (wt%)	Figure	SAE (wt%)
-25% to Feed	5.7	18.43	5.27	19.70	5.31	26.27
Return to S.S.	5.8	14.00	5.28	14.90	5.32	9.93
+25% to Feed	5.5	20.72	5.29	18.76	5.33	9.17
Return to S.S.	5.6	26.04	5.30	20.51	5.34	8.41

The results given are for STC runs that already have 'good' parameter estimates. Except for the -25% step decrease in feed flow rate from its steady state value, the STC with feedforward control action improves the bottom

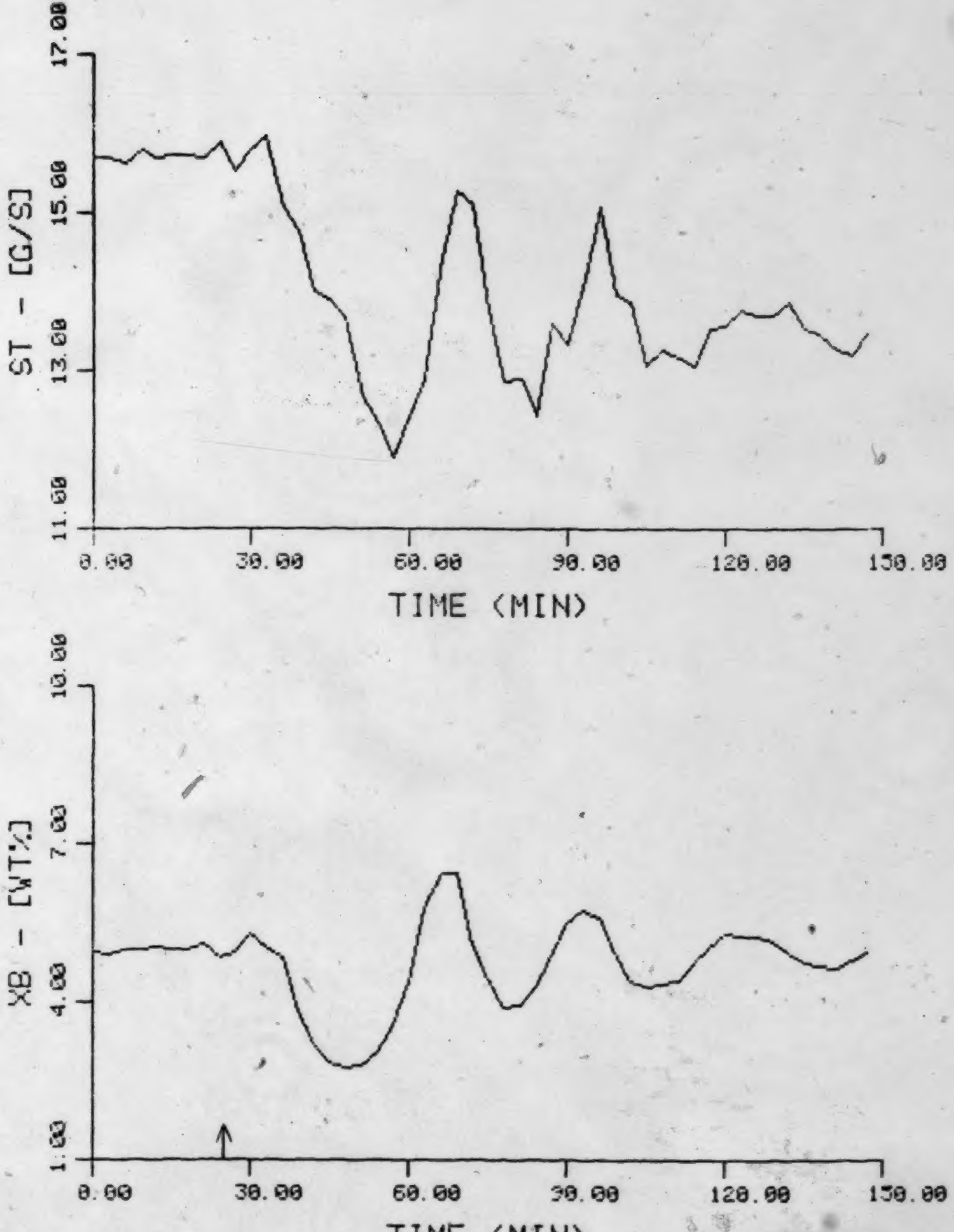

Figure 5.31 STC + FF Control of Bottom Composition for a -25% Step Change in Feed Flow Rate With Q-WT (k_p - 0.90 and k_i - 0.47)

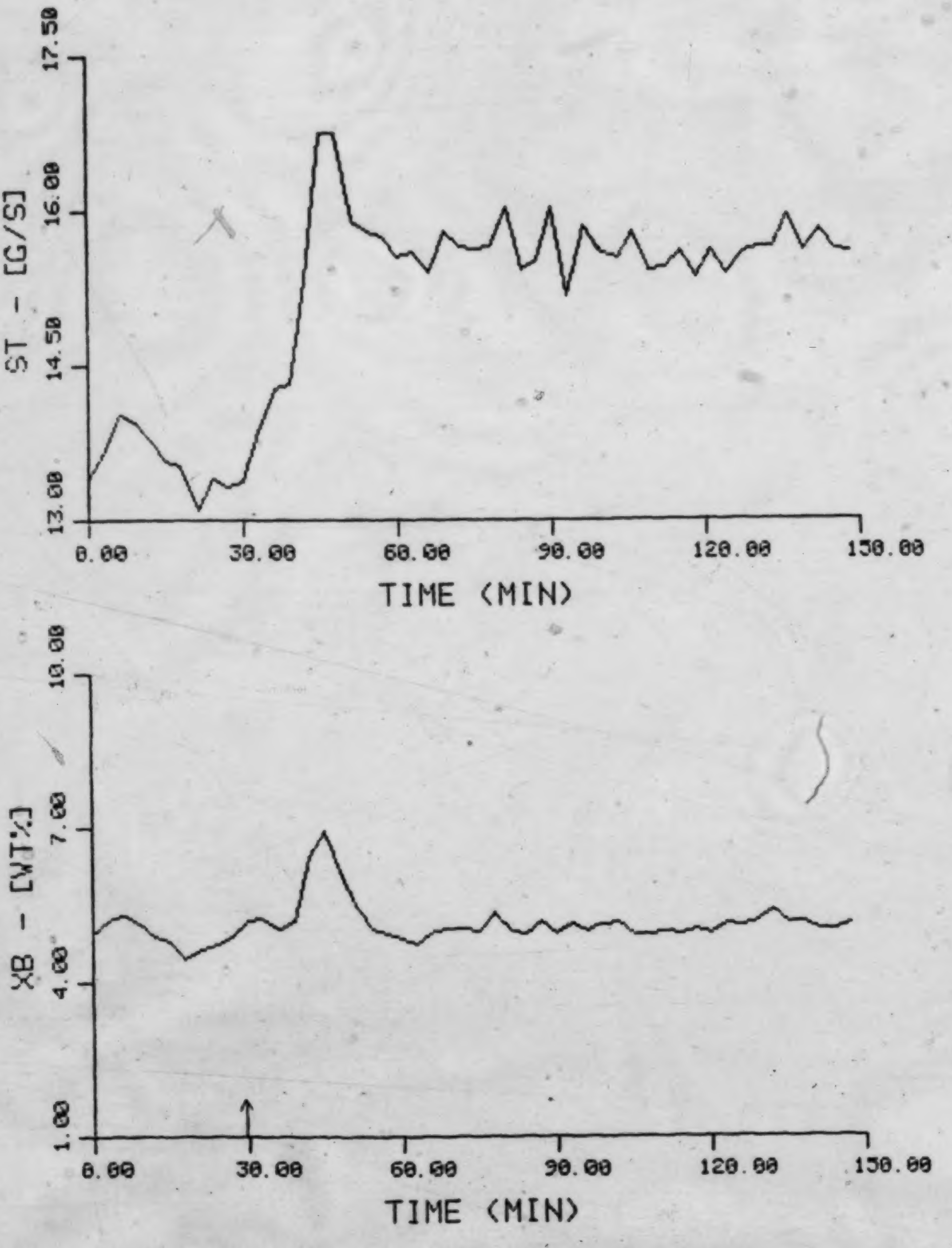

Figure 5.32 STC + FF Control of Bottom Composition for a Step Increase in Feed Flow Rate to its Normal Steady State Value With Q-WT (k_p - 0.90 and k_i - 0.47)

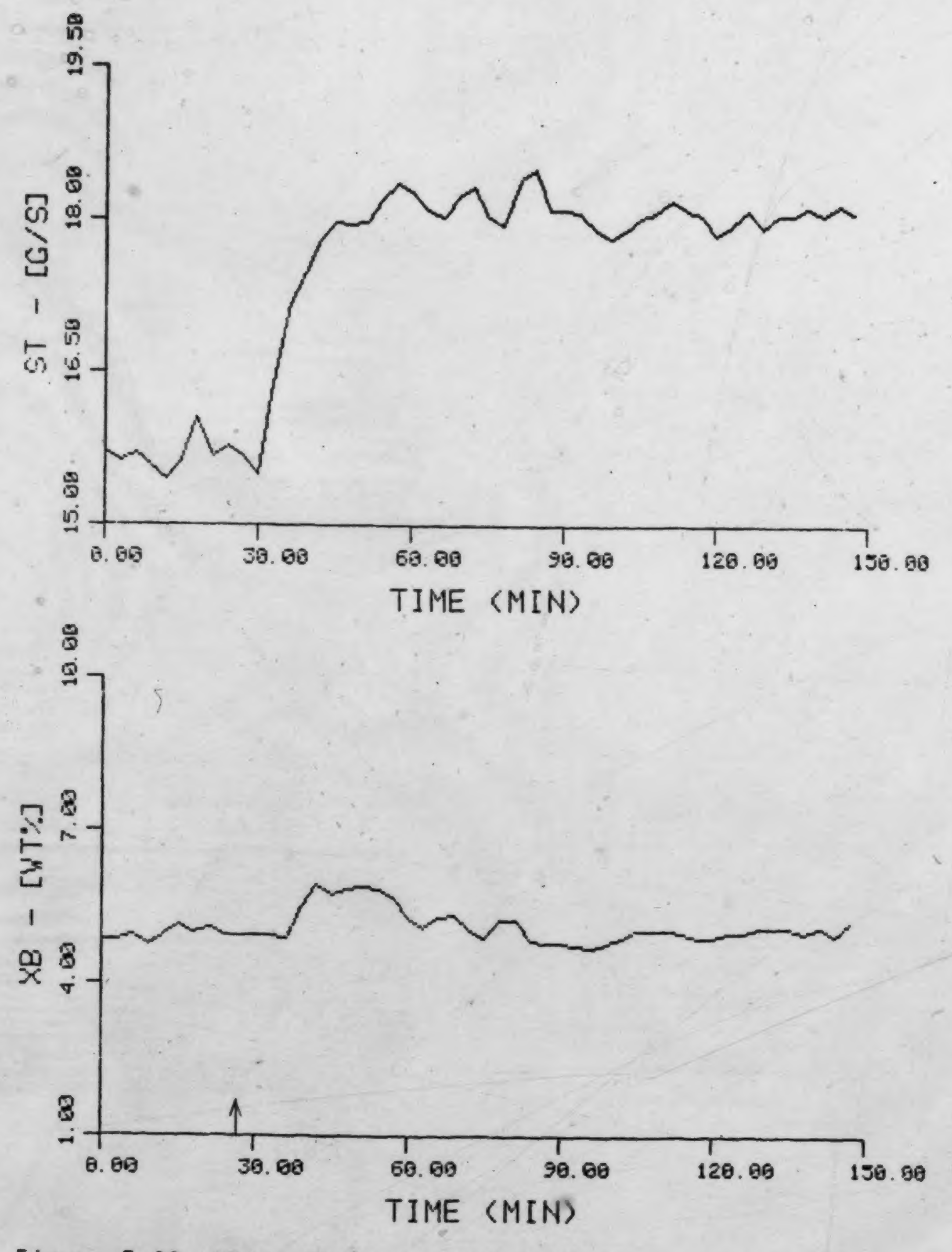

Figure 5.33 STC + FF Control of Bottom Composition for a +25% Step Change in Feed Flow Rate With Q-WT (k_p - 0.90 and k_i - 0.47)

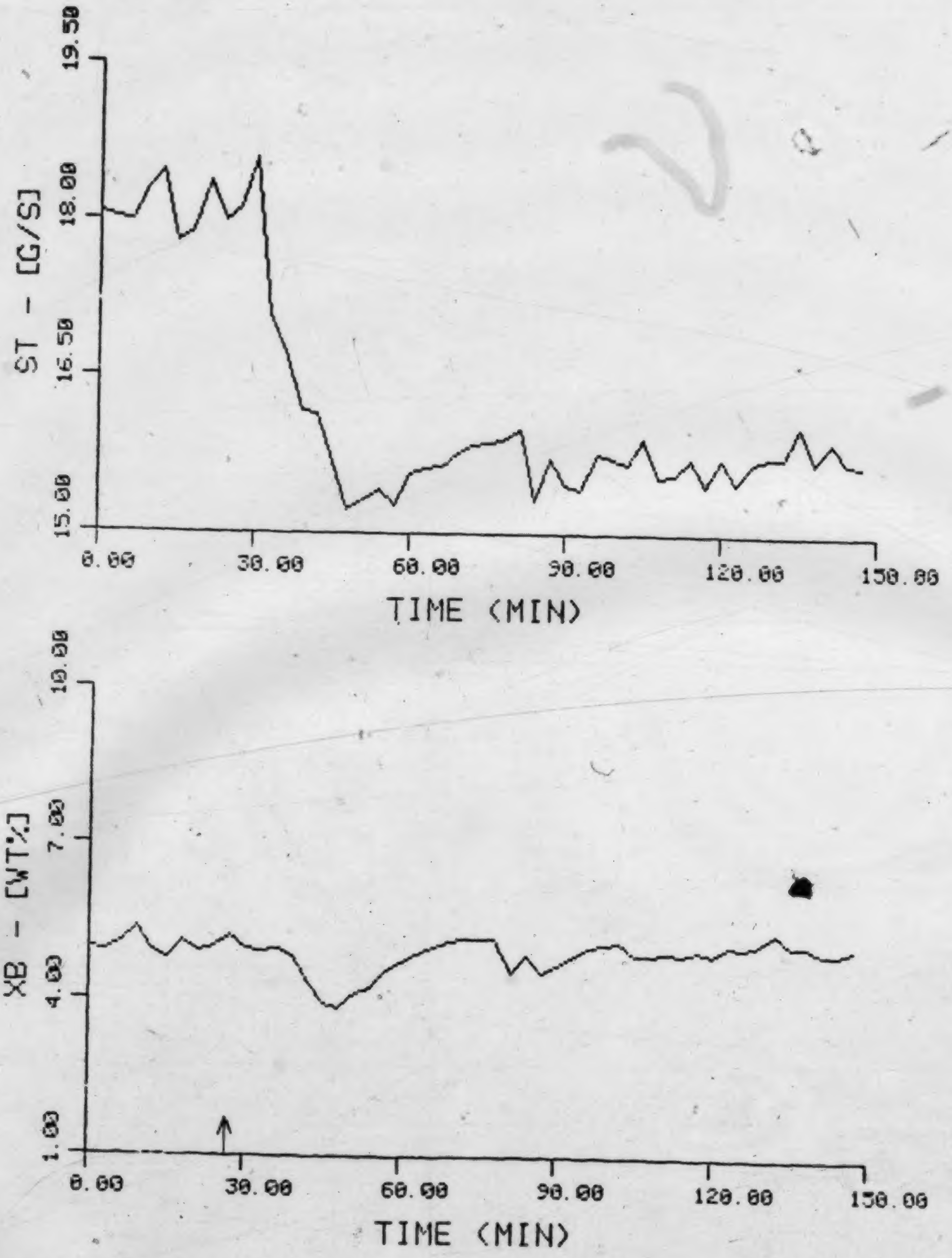

Figure 5.34 STC + FF Control of Bottom Composition for a Step Decrease in Feed Flow Rate to its Normal Steady State Value With Q-WT (K_p - 0.90 and K_i - 0.47)

composition control significantly. The error values using feedforward are almost one-half of those values obtained when feedforward control action was not used. The self-tuning controller did not perform better than the PID controller for the -25% step decrease from the steady state feed flow rate because the feedforward terms have not had time to be identified.

5.7 SIMULTANEOUS CONTROL OF TERMINAL COMPOSITION

Simultaneous control of overhead and bottom compositions using the self-tuning controller was carried out for each of the different feed disturbances. The terminal compositions were controlled using two separate STC (multiloop configuration, ML-STC) and two STC that were linked by feedforward terms to cancel the effect of interaction (multivariable configuration, MV-STC).

5.7.1 Multiloop Self-Tuning Control of Terminal Composition

The original controller parameters and options for the two separate self-tuning controllers are given in Table 5.9. The intial parameters values are the final estimates from the single composition control tests.

After an intial identification period, the feed disturbance is introduced. It was found that the top loop Q-weighting had to be de-tuned to prevent oscillatory behavior. The composition behavior, for the de-tuned Q-weighting test for the -25% step decrease from the steady

Table 5.9 Controller Parameters and Options for Multiloop and Multivariable STC

Identification Scheme : Recursive Square root (top and bottom)

G Polynomial : EB (top and bottom)

Number of Parameters :

Top	Bottom
NG1 = 3	NG1 = 4
NF = 2	NF = 3
ND = 0	ND = 5 (FF added)
NH = 1	NH = 1
NG2 = 2 (MV-STC)	NG2 = 3 (MV-STC)
K1 = 1	K1 = 2
K2 = 0 (MV-STC)	K2 = 0 (MV-STC)
K3 = 0	K3 = 1 (FF added)

Parameter fixed : $h_o = -1$ (top and bottom)

Initial Value of Parameters :

Top		Bottom		
G1	F	G1	F	D
0.2090	0.7382	0.1586	1.0340	0.03257
-.0409	0.1161	0.0548	0.1695	0.04689
-.0834		-.0997	-.6200	0.00937
		-.0763		-.03920
				-.03590

Q-weighting :

	Top	Bottom	
k_p =	3.676	1.145	(g/s)/wt%
k_i =	0.919	0.226	(g/s)/wt%

P-weighting : Set to 1 (top and bottom)

Sampling Interval: 3 minute (top and bottom)

Forgetting Factor: 0.99 (top and bottom)

Initial $\underline{\underline{P}}^c$ Matrix : $0.01\underline{\underline{I}}$ (top and bottom)

Incremental Control Limit :

Top	Bottom
2.30 g/s	2.25 g/s

state feed flow rate and the subsequent return to the normal value are shown in Figures 5.35 and 5.36. The control performance that was obtained with feedforward control action added to the bottom STC is shown in Figures 5.37 and 5.38. A summary of the absolute error values over a period of 30 samples after the feed flow rate disturbance was introduced is given in Table 5.10.

Table 5.10 Summary of Top and Bottom Composition Absolute Error Values for Multiloop STC With and Without Feedforward (FF) added

		Type Of Disturbance					
		-25% to Feed		Return to S.S.		+25% to Feed	
Type of Control		Figure	SAE (wt%)	Figure	SAE (wt%)	Figure	SAE (wt%)
ML - STC	top	5.35	2.32	5.36	2.17		
	bot	5.35	23.75	5.36	19.71		
ML - STC + FF	top			5.37	3.74	5.38	2.27
	bot			5.37	14.59	5.38	8.97

The SAE values show that the control performance of the multiloop self-tuning controller was comparable to that of the well tuned PID compensator. It should be noted that as with bottom composition control, implementation of the STC required much less tuning than was the case for the PID regulator. In fact, the Q-weighting for the bottom composition STC was not re-tuned, from the single loop values, for use with multiloop control. In addition, proportional, integral and derivative actions are involved in the PID compensator while only proportional and integral

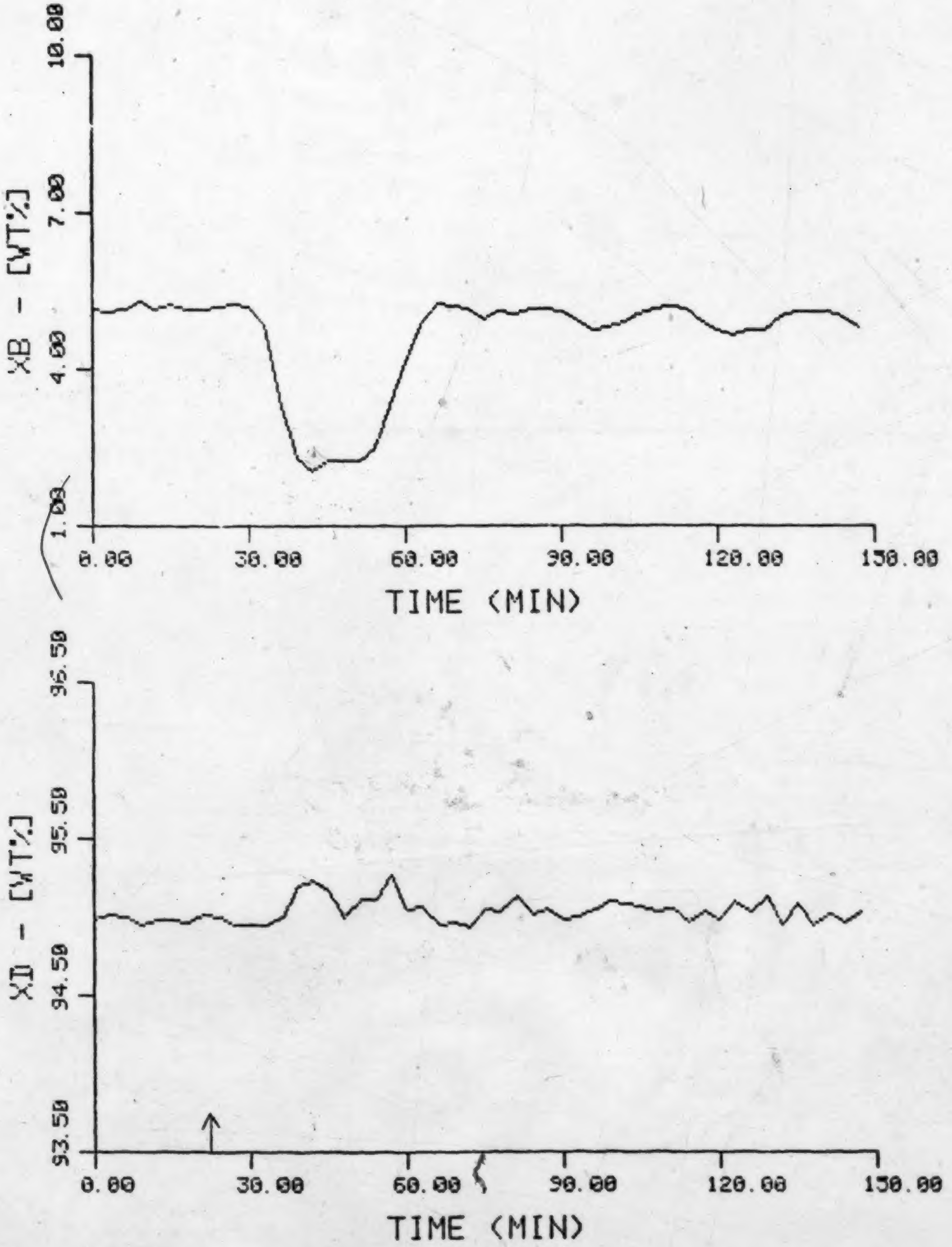

Figure 5.35 ML-ST Control of Terminal Compositions for a -25% Step Change in Feed Flow Rate With Q-WT (top: k_p - 2.7 k_i - .45 bot: k_p - .90 k_i - .47)

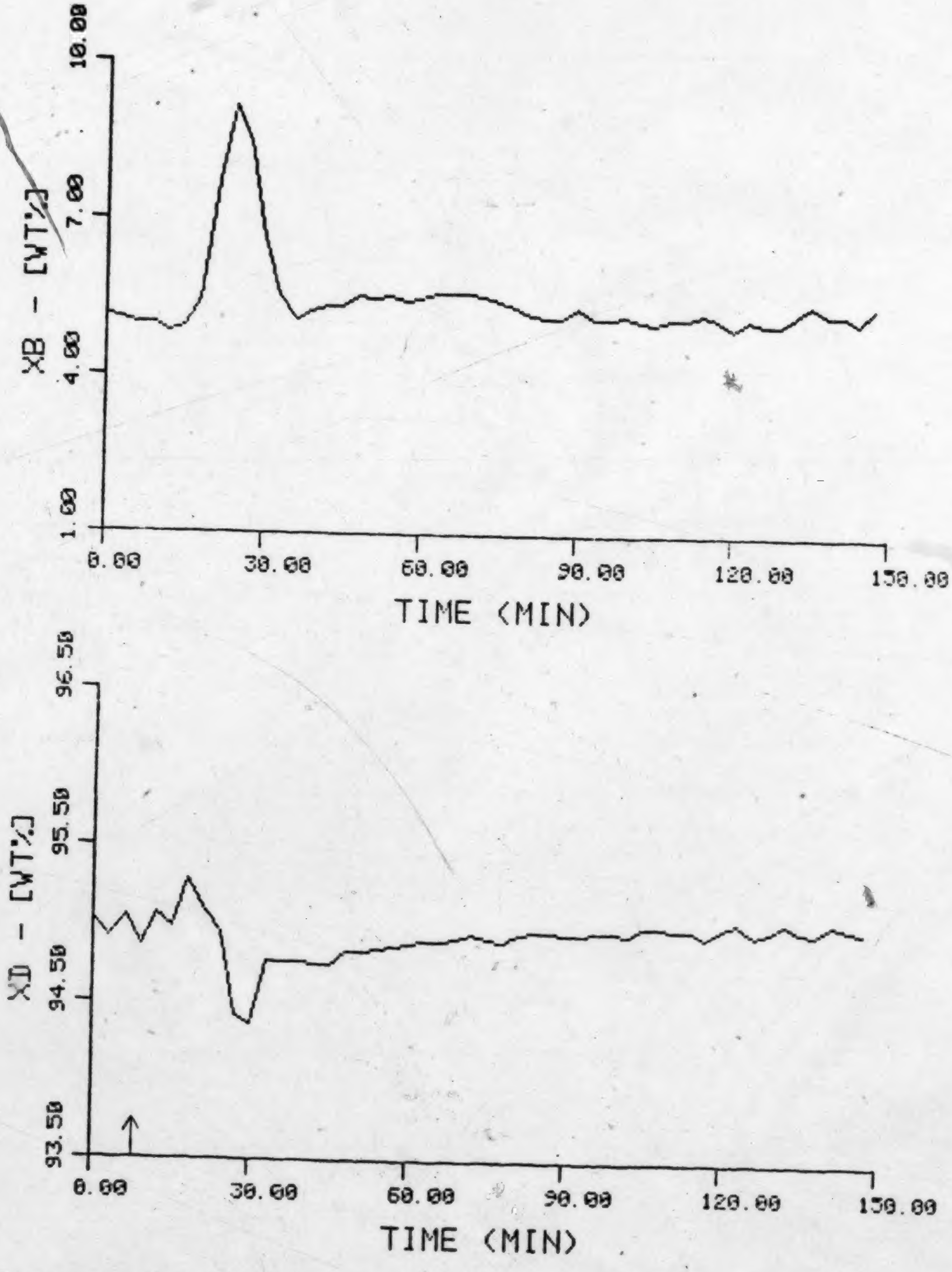

Figure 5.36 ML-ST Control of Terminal Compositions for a Step Increase in Feed Flow Rate to its Normal Steady State Value With Q-WT (top: K_p - 2.7 k_i - .45 bot: k_p - .90 k_i - .47)

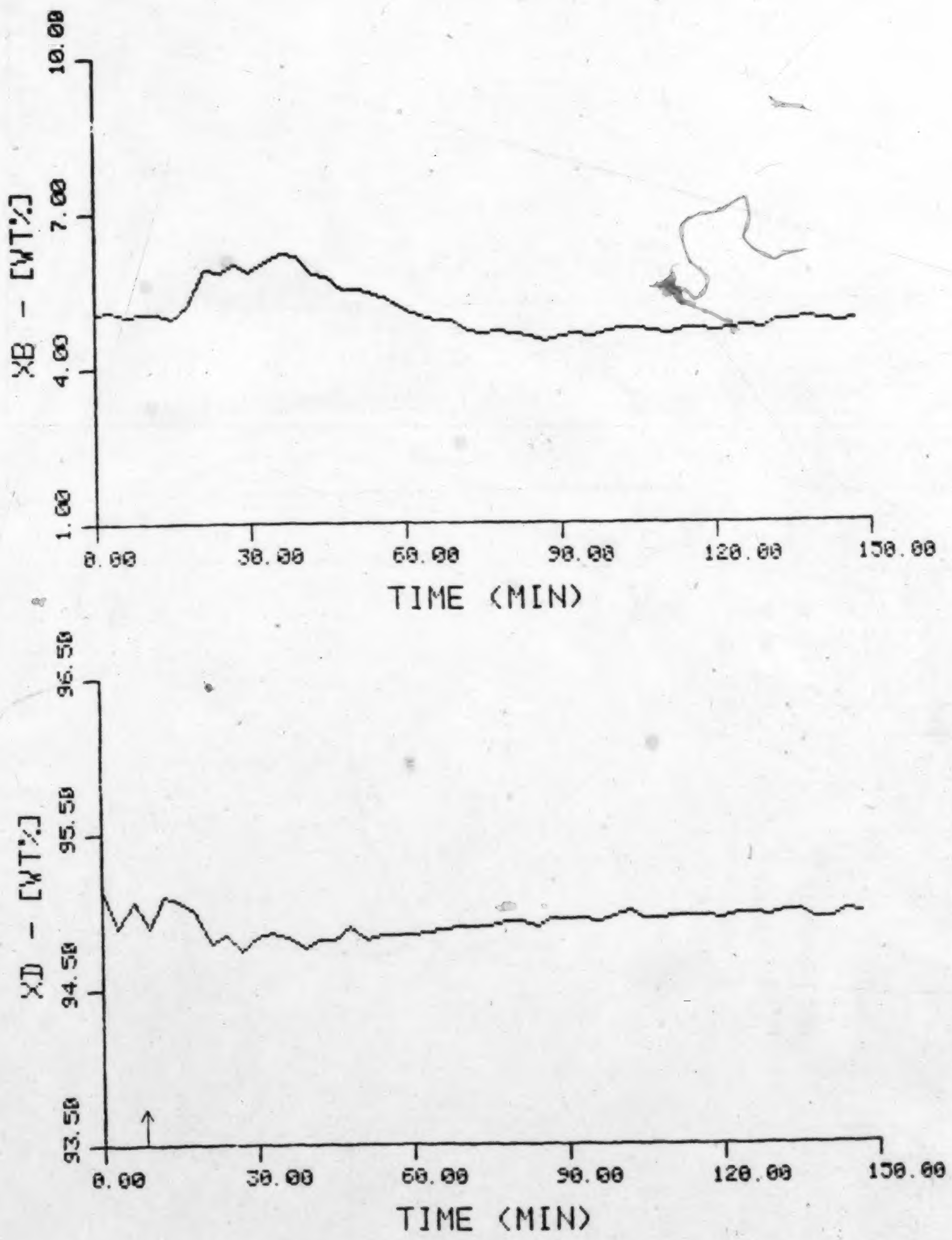

Figure 5.37 ML-STC + FF (bottom) Control of Terminal Compositions for a Step Increase in Feed Flow Rate to its Normal Steady State Value With Q-WT (top: K_p - 2.7 K_i - .45 bot: K_p - .90 K_i - .47)

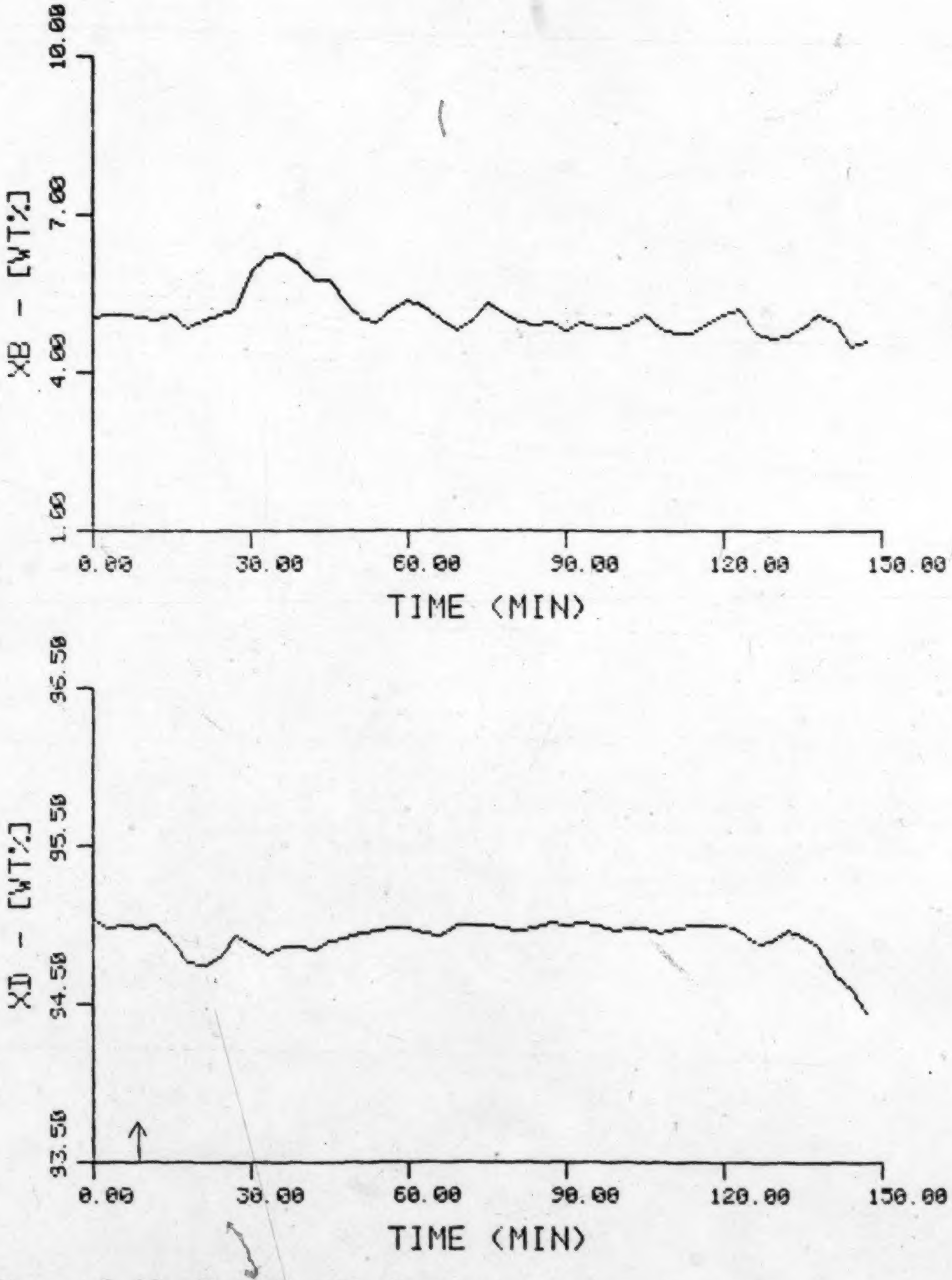

Figure 5.38 ML-STC + FF (bottom) Control of Terminal Compositions for a +25% Step Change in Feed Flow Rate With Q-WT (top: K_p - 2.7 K_i - .45 bot: K_p - .90 K_i - .47)

actions are used with the Q-weighting of the self-tuning controller. The STC response should improve if derivative action is added.

The addition of feedforward action for the bottom self-tuning controller has significantly improved the control performance as can be seen by examining the SAE values in Table 5.10. The bottom composition SAE values are greatly reduced while the top composition SAE values for the STC are comparable to the values that result with PID control.

5.7.2 Multivariable ST-Control of Terminal Composition

A multivariable STC was also used to control the terminal compositions. The original parameters and options used by the multivariable STC are the same as those in Table 5.8 except that the feedforward linkage terms (G2) are identified. The composition responses for the 25% step decrease in feed flow rate and the subsequent increase in feed flow rate to return the flow to the normal steady state value are given in Figures 5.39 and 5.40.

The absolute error values for these responses and those of the multiloop STC and PID control are given in Table 5.11. These error values show that the multivariable STC performed as well as the PID compensator for bottom composition control, but provided significantly better control of top composition control than did PID control. The top composition error values with multivariable STC are

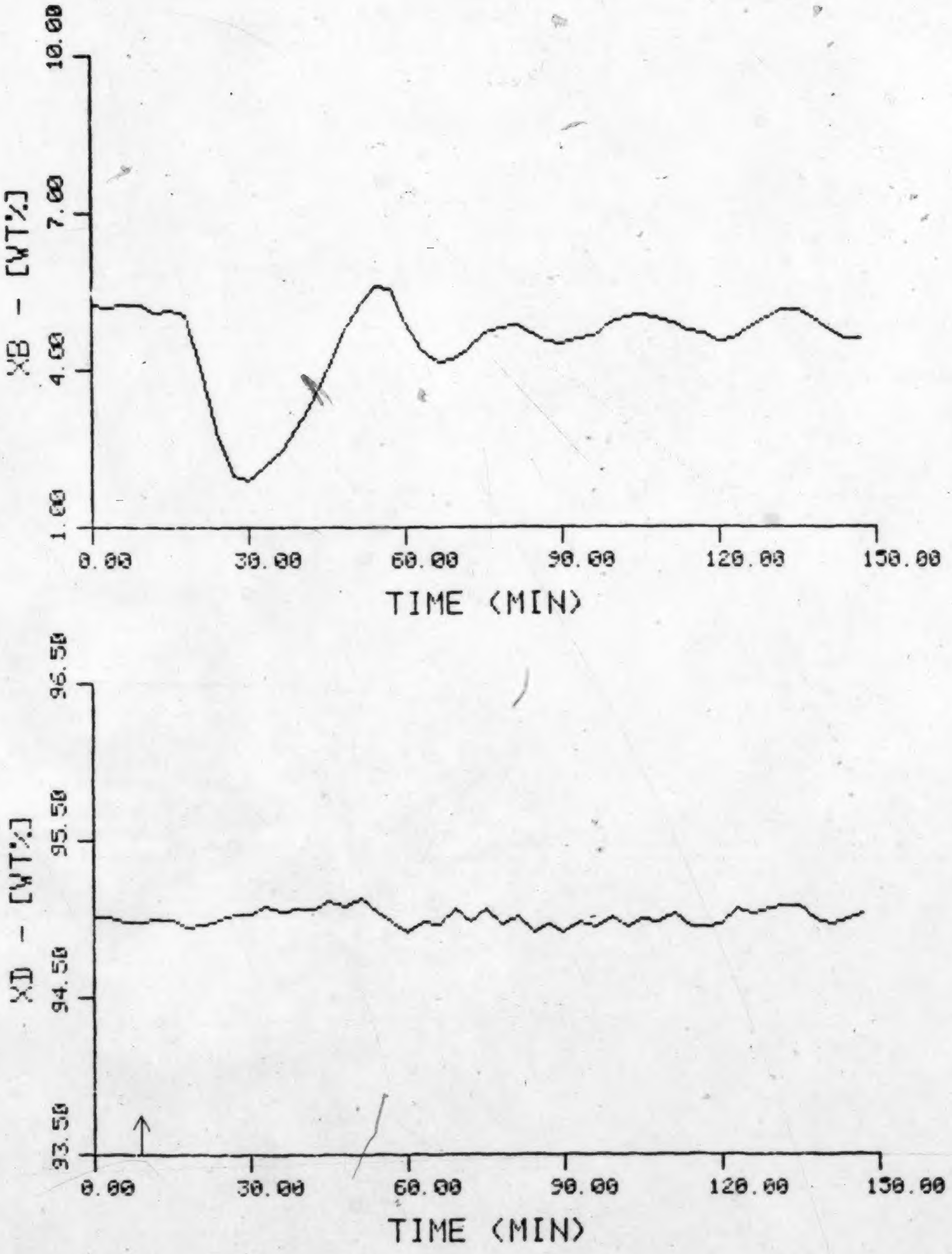

Figure 5.39 MV-ST Control of Terminal Compositions for a -25% Step Change in Feed Flow Rate With Q-WT (top: k_p - 1.5 k_i - .23 bot: k_p - .90 k_i - .47)

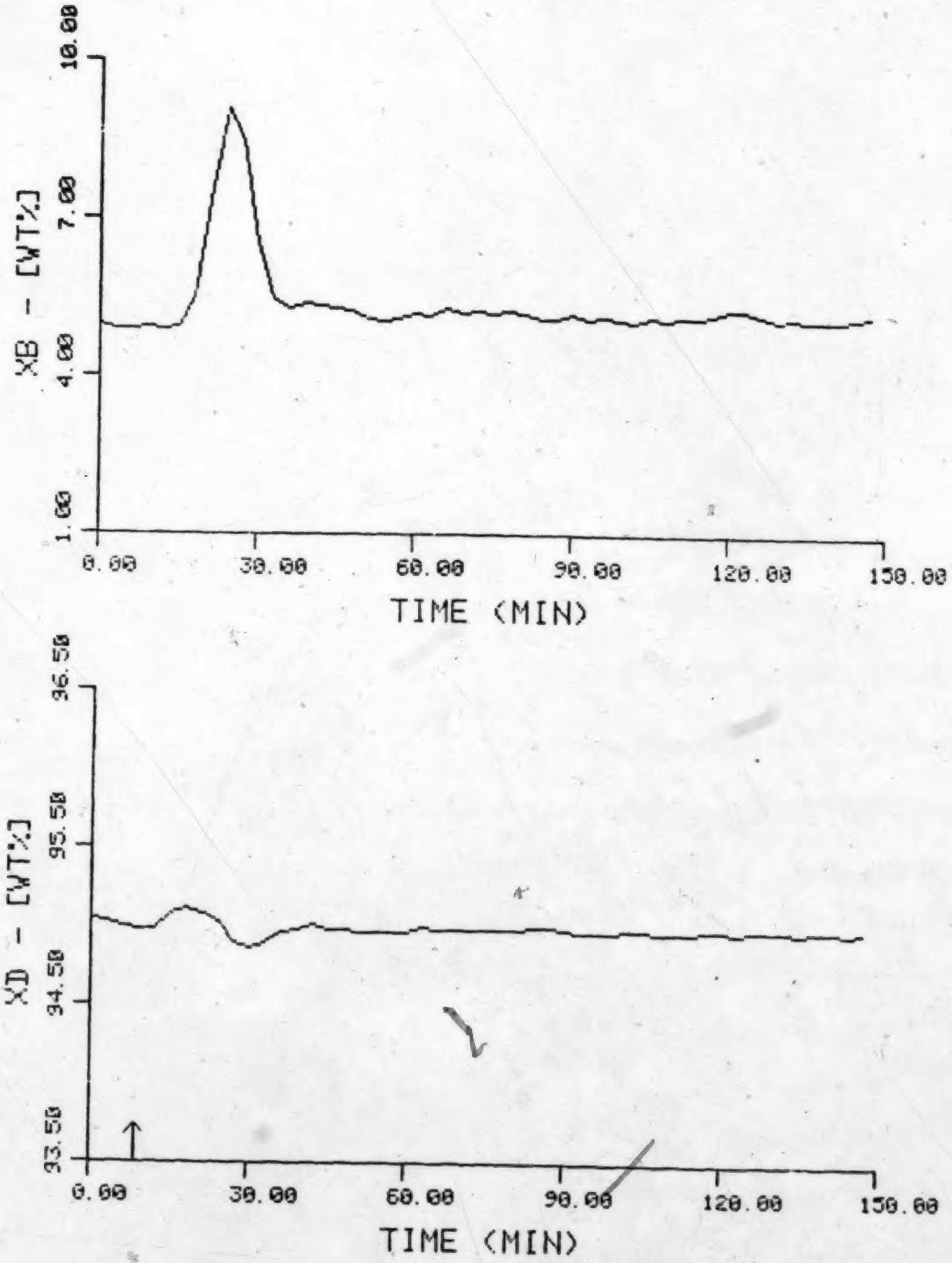

Figure 5.40 MV-ST Control of Terminal Compositions for a Step Increase in Feed Flow Rate to its Normal Steady State Value With Q-WT (top: k_p - 1.5 k_i - .23 bot: k_p - .90 k_i - .47)

about one-half the values that result using PID control. The improvement is due to the addition of the feedforward terms which link the two controllers and serve to reduce interaction hence improving control.

Table 5.11 Comparison of Top and Bottom Composition Absolute Error Values for Multiloop PID, Multiloop STC (With and Without FF), and Multivariable STC

		Type Of Disturbance					
		-25% to Feed		Return to S.S.		+25% to Feed	
Type of Control		Figure	SAE (wt%)	Figure	SAE (wt%)	Figure	SAE (wt%)
ML - PID	top	5.11	2.13	5.12	2.30	5.9	2.75
	bot	5.11	21.69	5.12	22.96	5.9	27.26
ML - STC	top	5.35	2.32	5.36	2.17		
	bot	5.35	23.75	5.36	19.71		
ML - STC + FF	top			5.37	3.74	5.38	2.27
	bot			5.37	14.59	5.38	8.97
MV - STC	top	5.39	1.38	5.40	1.07		
	bot	5.39	27.39	5.40	17.28		

5.8 DISCUSSION OF RESULTS

From the results given, it has been shown that the feedback self-tuning controllers can control the terminal compositions of the distillation column as well as or better than well tuned PID compensators. With the multivariable STC, the top composition controller is able to react immediately to steam changes hence improving the top composition control compared to the multiloop PID case.

The ability of the feedback STC to provide a control performance that is comparable to a PID compensator is remarkable considering the type of disturbance used to compare the controllers. The use of step changes in feed flow rate as disturbances is a very severe test. In the derivation of the STC, the disturbances have been assumed to have zero mean. When a step change in the feed flow rate is introduced, a new steady state control output is required, as calculated from the control law. Therefore, the feed flow step changes are not zero mean disturbances. To further appreciate this situation, consider what happens to the STC when the feed rate is increased. As the additional flow of material moves through the column, the bottom methanol composition starts to increase and the STC compares the composition with the predicted value and finds there is an error. The controller will then increase the steam flow rate and in addition change the parameters so that they will give a prediction consistent with the higher recorded value. As more of the increased feed reaches the reboiler, the composition becomes even higher, the steam flow rate is again increased and the parameters further changed to give the correct output. In effect, there is a transition period when the parameters change and the predicted outputno longer matches the actual output. Figures 5.41 and 5.42 show how the bottom STC parameters change when a -25% step change in feed flow rate occurs (run shown in Fig 5.27). It is seen that there is a significant change in the parameter

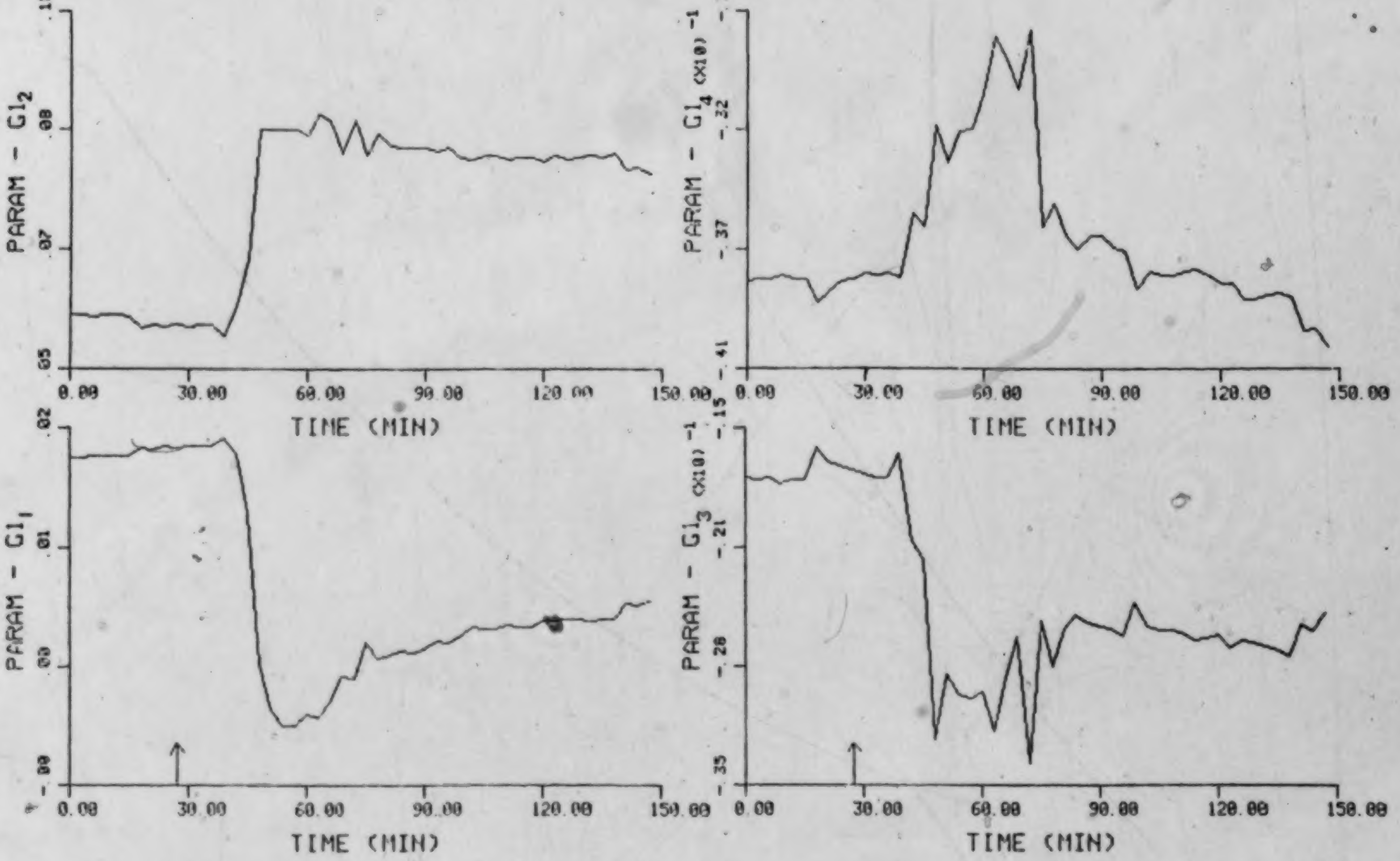

Figure 5.41 Variation of G1 Parameters in the Transition Period of a -25% Step Change in Feed Flow Rate for the Bottom STC with Q-WT

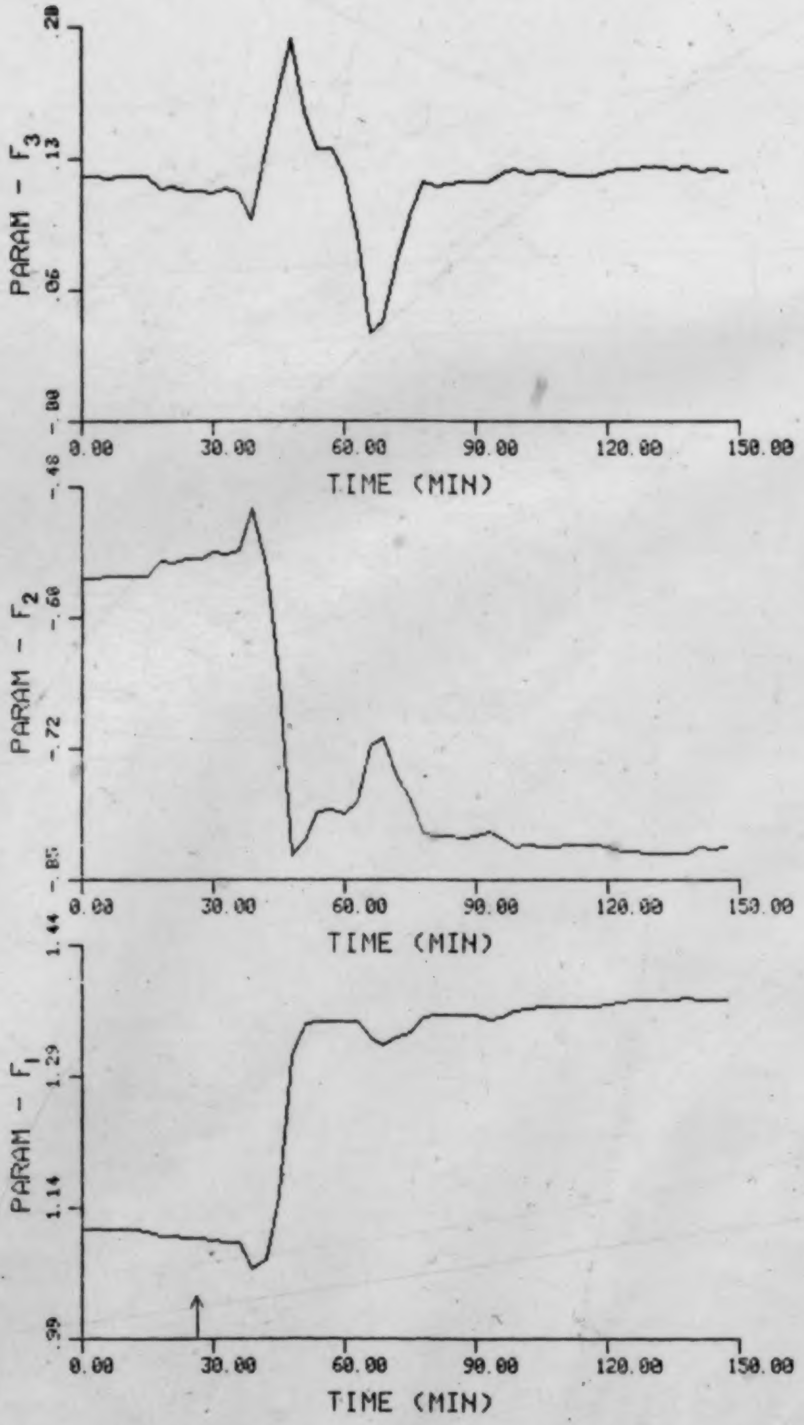

Figure 5.42 Variation of F Parameters in the Transition Period of a -25% Step Change in Feed Flow Rate for the Bottom STC with Q-WT

estimates. It is due to the robustness of the STC that using only feedback information, it is able to match the control performance of the well tuned PID. To properly handle step changes in feed flow rate, the feedforward option should be used. The results of the self-tuning controller with feedforward added does indeed show considerable improvement over the PID case.

It should also be noted that the PID control behavior shown has been obtained after considerable time was spent fine tuning the compensator. On the other hand, the amount of time needed to tune the Q-weighting was minimal. The original estimates obtained from Halman's technique [75] gave good control. With more tuning of the Q-weighting, it should be possible to improve the control performace. Additional improvement in the controller performance should also be realized if derivative action is added into the Q-weighting.

6. CONCLUSIONS AND RECOMENDATIONS

This work was concerned primarily with the experimental evaluation of the self-tuning controller. However, before the evaluation could be carried out, the pairing of manipulated and controlled variables had to be decided. The main concern was whether top composition should be controlled by manipulating reflux flow (energy balance control) or distillate flow (material balance control). It was found that compared to energy balance control, the material balance control strategy is not as sensitive to heat disturbance provided the external reflux ratio is large. However just the reverse case is true if the external reflux ratio is small. Analysis of the sensitivity of the vapor-to-liquid ratio to changes in the vapor rates for the two strategies provides valuable information on which of the two control schemes should provide better control performance for heat disturbances entering the column. For the pilot plant distillation column used in this work, analysis of the vapor-to-liquid ratio indicated that energy balance control was superior and this was substantiated by the results from experimental tests.

To evaluate the STC, a comparison was made between the performance of the STC and a well tuned PID compensator in controlling the terminal compositions of the pilot plant column when it was subjected to step changes in the feed rate. The evaluation was carried out for: top composition control, bottom composition control and dual composition control. In all cases, it was found that the STC is superior to the PID compensator. Specifically, it has been shown that:

(1) The STC acting only in the feedback mode using initial Q-weighting estimates from Halman's [75] technique performed as well as a PID compensator that had been very well tuned at a considerable expenditure of time.

(2) Addition of feedforward control action on the bottom composition loop significantly improved the controller performance.

(3) Use of the multivariable STC allowed the top composition controller to react immediately to changes in heat input hence improve top composition control performance.

In addition, the STC was found to have the following properties:

(1) Starting with zero estimates, the STC can, for a fast system (top composition loop), converge to reasonable estimates after only 30 sampling intervals. It gives superior control compared to PID control results when the STC is used with these estimates.

(2) Fixing the h_0 parameter value to -1 does not create any problems with parameter convergence.

(3) The addition of Q-weighting reduces the variation in the manipulated variables and as a result the control of the output variable is improved considerably.

(4) The controller parameters are able to readjust to some

degree for changes in the Q-weighting so that the output response is not as sensitive to changes in the Q-weighting constants as in the case of the PID compensator. Nevertheless, the Q-weighting can still be fine tuned the same way as a normal PI compensator is tuned to obtain even improved control responses. The relationship between K_p and K_i and how they affect the output response remains the same.

(5) If the identification phase of the STC is stopped, an unknown disturbance will cause an offset to occur. The magnitude of the offset depends upon the sum of the F and G parameters.

(6) To an extent, a large sampling time has the same effect as adding more Q-weighting; i.e., it smooths out the variation in the manipulated variable. However, if the STC is acting only in the feedback mode, the controller response will suffer because it reacts more slowly to unknown disturbances due to the larger sampling time.

In summary, the experimental evaluation of the self-tuning controller as modified by Morris [24] has shown that the controller is superior to the PID compensator. If tuning is necessary, the controller can be fine tuned the same way a PID regulator is tuned. The controller is extremely robust as it is able to handle non-zero mean disturbances even though the control law was derived based on the assumption that the disturbance is a white noiise sequence.

From the results of this work, the following recommendations are given for possible future studies:

(1) With the present column operating conditions, energy balance control has been shown to be superior. It is recommended that test be performed with the operating conditions altered so that the external reflux ratio is higher. This would indicate whether material balance control will indeed be less sensitive to heat disturbances under the new operating conditions.

(2) While performing the experimental work for this study, observations on the multipoint temperature chart recorder indicated that the liquid temperature on tray 1 gave a good indication of changes in bottom composition. It is suggested that bottom composition be controlled by maintaining tray 1 temperature constant using the self-tuning controller. For a binary system, providing the pressure is constant, fixing the temperature implies that the composition will remain constant. To account for any variation in pressure, the result of the GC analysis can be used to reset the tray 1 temperature set point.

(3) The self-tuning controller is designed primarily to handle stochastic disturbances while the evaluation has been carried out using deterministic disturbances. A further evaluation should be made on how the performance of the STC compares with the PID compensator when random disturbances are used; e.g.,

add noise to the composition measurements.

(4) When an unknown deterministic disturbance is encountered, the STC forces the parameters to change rapidly to account for the disturbance. An improved response might be achieved by freezing the parameters once reasonable estimates have been obtained. To prevent the offset that occurs when identificaton is stopped, an integrator can be added to the controller. The control action would be the normal STC algorithm output plus an added action based on the error from set point.

(5) In the present implementation of the STC algorithm, the feedforward control action option only allows the use of lead terms. As lag action is normally required in feedforward compensation, it should be added into the algorithm.

(6) This study considered the performance of the self-tuning controller only for load disturbances. Additional testing should be performed to study the performance of the controller for set point changes.

(7) The multivariable approach given by Morris [24] which is used in this study differs from that proposed by Keviczky [19] and Borrison [19] in that the identification of the system is performed on a loop by loop basis. Both Keviczky and Borrison suggested identifying the multivariable model directly. A direct comparison by simulation or experimentally of these

different multivariable self-tuning schemes should be undertaken.

(8) Rather than starting with zero initial estimates, it is suggested that the STC be allowed to identify parameter estimates while the process is operating under PID control. These estimates should provide a smooth transition during the initial switch to the self-tuning controller.

(9) The problem of the covariance matrix bursting due to inadequate excitation should be investigated. The different methods that have been proposed to overcome the problem should be tested; eg. use of recursive learning identification as proposed by Morris [24].

NOMENCLATURE

a. Abbreviations:

DACS - Data Acquisition Control and Simulation
DDC - Direct Digital Control
FF - FeedForward
GC - Gas Chromatograph
HP - Hewlett Packard
ML - Multiloop
MV - Multivariable
PID - Proportional-Integral-Derivative
Q-WT - Q-weighting
SAE - Sum of Absolute Error
SISO - Single Input Single Output
STR - Self-Tuning Regulator
STC - Self-Tuning Controller
S.S. - Steady State

b. Variables:

D - Distillate flow rate
FE - Feed flow rate
J - Cost function for SISO case
J - Cost function for multivariable case
I - Identity matrix
k - System time delay in integer sample intervals.
k^A - Time delay due to other output for a multivariable system

k^B - Time delay due to other control input for a multivariable system

k^L - Time delay associated with load disturbance

k_p - Proportional constant in PID compensator

k_i - Integral gain in PID compensator

k_d - Derivative gain in PID compensator

$\underline{K}$ - Kalman gain vector used in parameter estimation algorithm

K1 - Use in STC program to designate time delay of system

K2 - Use in STC program to designate time delay due to other control input for a multivariable system: $k^L_{ij} - k^B_{ii}$

K3 - Use in STC program to disignate time delay associated with load disturbance: $k^L - k$

L - Liquid rate inside the column

M - Number of loops in multivariable system

n - System order

ND - No. of D parameters in controller

NG1 - No. of G1 parameters in controller

NG2 - No. of G2 parameters in controller

NF - No. of F parameters in controller

NH - No. of H parameters in controller

$\underline{\underline{P}}^c$ - Covariance Matrix

RE - Reflux flow rate

ST - Steam flow rate

t - Time measured in integral sample intervals

u - Control input

V - Vapor rate inside the column

v - Load disturbance

$\bar{v}$ - Modified load disturbance defined as $z^{k-k^L}v$

w - Set point

$\bar{w}$ - Modified set point defined as Hw

$\underline{X}$ - Vector containing measured data

XB - Bottom Composition in WT% methanol

XD - Overhead Composition in WT% methanol

y - System output

$\bar{y}$ - Modified system output defined as y/P_d

z^{-1} - Backshift operator; $z^{-k}u_t = u(t-k)$

c. Greek:

ε - Weighted output prediction error

ξ - Uncorrelated zero-mean random input

ϕ - Scalar output function

$\underline{\theta}$ - Vector of controller parameters: F, G, H, D

ρ - Forgetting factor

σ - Variance

d. Polynomials in z^{-1}:

A - Order N corresponding to system output, $a_0 = 1$

B - Order N corresponding to control input, $b_0 = 0$

C - Order N corresponding to random disturbance, $c_0 = 1$

D - Associated with load in final control law

E - Use to separate past and future disturbance

F - Use to separate past and future disturbance

G - Associated with control input in the final control law

H - Associated with set point in the final control law

L - Order N corresponding to deterministic load disturbance input, $l_0 = 1$

P - Weighting function on system output

Q - Weighting function on system input

R - Weighting function on set pont

e. Superscript:

' - Indicates polynomials used for derivation of STC for the case without weighted output

^ - Estimates of the parameters

* - Predicted value

T - Transpose of Matrix

f. Subscript:

ij - For the multivariable case, denotes the jth component of the ith loop

N - Numerator of a z transfer function

D - Denominator of z transfer function

t - Value at present time

t+k - Value at k samples from present time

9. Symbols:

[ ] - Use to designate the variables when extending the results to the multivariable system. When used with polynomials in z , the result is a polynomial matrix in z . When used with scalars, the results in a vector.

_ - Designates a vector

= - Designates a matrix

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APPENDIX A

DETAIL SCHEMATIC OF PILOT SCALE DISTILLATION COLUMN

LEGEND:

$\frac{\text{TYPE}}{n}$ - indicates local analog equipment
TYPE - gives function
TYPE CODES
T - transmitter
R - recorder
C - controller
I - indicator
F - flow
A - concentration (analyzer)
T - temperature
P - pressure
DP - differential pressure
n - identification number

HXn - heater exchanger
n - identification number

GC - gas chromatograph

TC - thermocouple

UT - indicates utilities
UT - ST - 60 psig steam
- CW - cooling water

n - solenoid valve
n - identification number

– – – - control lines

——— - process lines

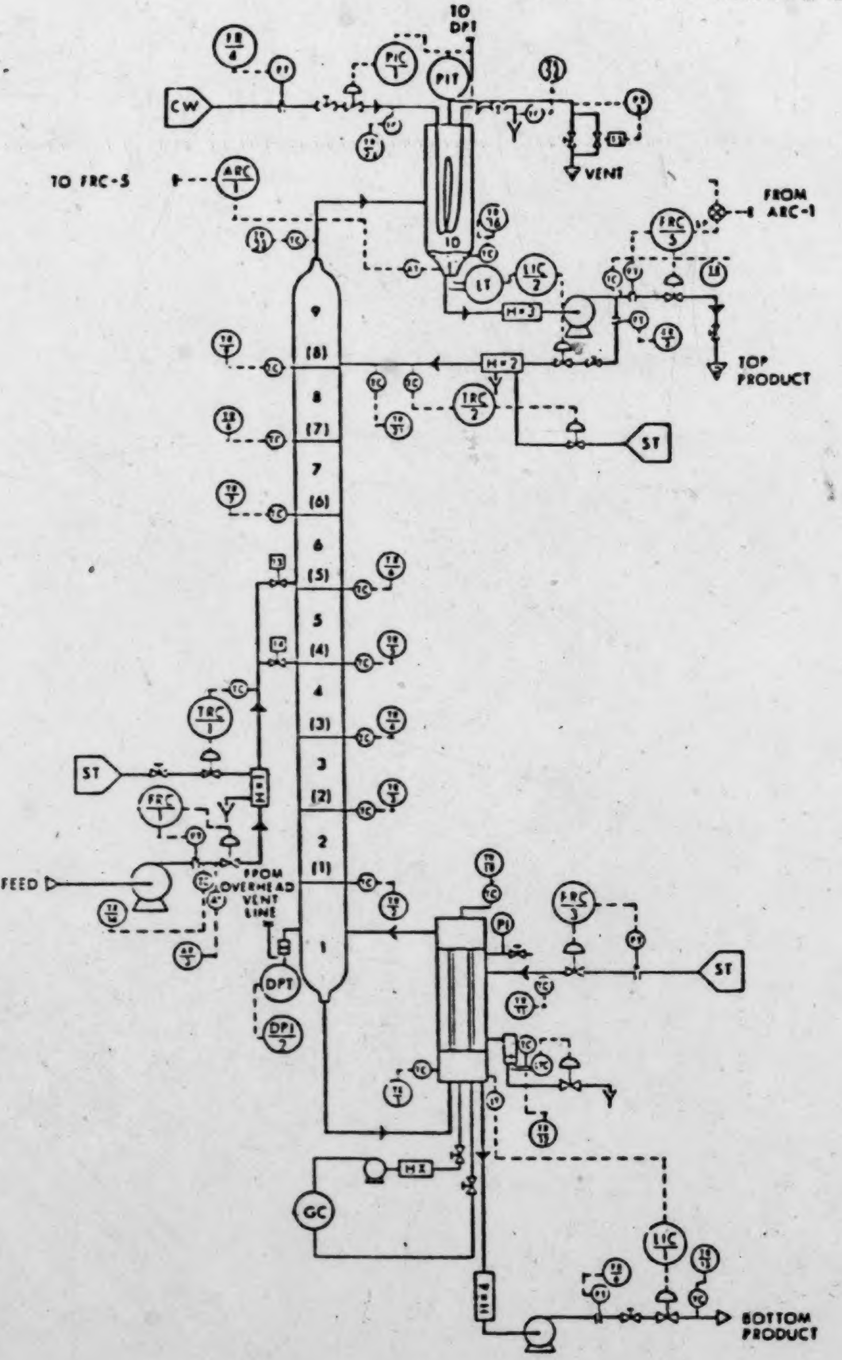
TO DPI
PIT
PIC 1
CW
VENT
TO FRC-5
ARC 1
FROM ARC-1
FRC 5
10
LT
LIC 2
H-3
TOP PRODUCT
H-2
TRC 2
ST
9
(8)
8
(7)
7
(6)
6
(5)
5
(4)
4
(3)
3
(2)
2
(1)
1
TRC 1
ST
FRC 1
FEED
FROM OVERHEAD VENT LINE
DPT
DPI 2
PI
FRC 3
ST
HX
GC
LIC 1
BOTTOM PRODUCT

Figure A.1 A Detailed Schematic of the Pilot Scale Distillation Column

APPENDIX B

SAMPLE CALCULATION TO OBTAIN INITIAL Q-WEIGHTING PARAMETERS

1. Using Halman's technique [75], the K_p and K_i are related to the process dynamics according to:

$$a = 1 + 0.5 * T_s/T_d \tag{B.4}$$

$$K = 2\tau/3K_G a T_s \tag{B.5}$$

$$a_0 = 1 + T_s/2\tau \tag{B.6}$$

$$a_1 = -(1 - T_s/2\tau) \tag{B.7}$$

$$K_p = -a_0 * K \tag{B.8}$$

$$K_i = (a_0 + a_1) * K \tag{B.9}$$

Where:

K_p = proportional gain constant in Q-wt
K_i = integral gain constant in Q-wt
K_G = Process gain
T_d = Process time delay
T_s = Sample time
τ = Process time constant

2. From results given by Kan [66], the bottom composition response for a 7 1/2% decrease in steam can be represented by a first order plus time delay model with constants:

K_G = 1.965 wt%/(g/s)
τ = 1000 second
T_s = 180 second
T_d = 316 second

3. From the discussion given in Chapter 2, it has been shown that the affect of the process time delay should be removed. So, the time delay is set equal to the sample time. Using the values given in section 2, the constants in section 1 become:

a = 1.5
K = 1.259
a_0 = 1.09
a_1 = -.91

The controller constants are then:

$k_p = 1.145$
$k_i = 0.226$

APPENDIX C

PROGRAMS LISTING

PROGRAM	DESCRIPTION	PAGE
STC	Implements the STC Algorithm on the Column	151
HSET	Sets Original Controller Parameters and Option	178
ERSUM	Computes Absolute Error Value of Data	186
HPLOT	Plots Data Stored in Files	188
GCLNK	Obtains GC Report from GC Computer	196
GCSCH	Process GC Report and Initiate GC Cycle	198
GCSWT	Reset Digital Switch That Initiate GC Cycle	201
BDC99	Monitors Column Operation	202

```
C
FTN4
      PROGRAM STC ( ,94) ,ST CONTROL MOD. BY HYL NOV. 1, 1979
      COMMON ICOM(1)
      DIMENSION IDCB2(144) , IDCB1(144) , IFILE(3) , IFILW(3)
      DIMENSION ICX(5) , IDX(6) , ERR1(2) , ERR2(2) , IPRAM(2)
       DIMENSION PERERR(2),YSTAR(2),USEND(2)
       DIMENSION YERR(2),DPR(2),BUF(56),ACLOSS(2)
       DIMENSION NSELF(2),N(2,6),ITYID(2),SAVE(2,11,30)
       DIMENSION WN(2),DN(2),YN(2),WO(2),WOLD(2),PHI(2)
       DIMENSION K1(2),K2(2),K3(2),UN(2),CA(2),CB(2),CO(2)
       DIMENSION NQ(2),QD(2,4),QN(2,4)
       DIMENSION NP(2),PN(2,4),PD(2,4)
       DIMENSION ITYW(2),IMW(2),HW(2),LW(2),BW(2)
       DIMENSION ITYD(2),IMD(2),HD(2),LD(2),BD(2)
       DIMENSION ITYCT(2),UNT(2),UBL(2),UTL(2),IRAMP(2),ACT(2)
       DIMENSION USS(2) , UPID(2)
       DIMENSION UPROP(2),UINT(2),UDINT(2),USINT(2),UDER(2)
       DIMENSION AKP(2) ,AKI(2) ,AKD(2) ,AKW(2),AKDN(2)
       DIMENSION AKPIS(2),AKPD(2),TS(2),UDIS(2)
       DIMENSION AKPS(2),AKIS(2),AKDS(2),ER1(2),ER2(2),SIAE(2)
       DIMENSION ADCC(2),ADCM(2),DACC(2),DACM(2),ITEST(2,8)
       DIMENSION KRS(16) , CHAR(5), ITIME(5), IOUTCH(2)
      DIMENSION X(2,30),PAR(2,30),P(2,210),G(2,30),ROW(2,3)
      DIMENSION IPIS(2),IP1(2),IP2(2),IFP(2,2),SADC(8)
C
C
      DATA NPARN/30/,NPMN/210/,NSCAN/5/,ISCAN/500/,
     *      CA , CB , CO / 2*1. , 4*0.0/,
     *     ICX/15,10,13,9,12/,
     *     ILG,IFILE/110,2H&N,2HDA,2HTA/,
     *     ITEST/16*0/,IOUTCH/7,8/,
     *     CHAR/4HINC ,4HSTQ ,4HSTI ,4HPOS ,4HMAN /
C
C
      CALL RMPAR(IPRAM)
      IWIO=IPRAM(1)
       IRIO = IWIO
C
C-------------------------------------------------------
C-
C-  OPEN UP FILE CONTAINING "ORIGINAL DATA".
C-
C
      ICR=136
    5 CALL OPEN(IDCB1,IERR,IFILE,0,77,ICR,144)
C
C-------------------------------------------------------
C-
C-  INITIALIZING CONSTANTS.
```

```
C-
C
         N=0
         DO   25 I=1,2
C
C
               AKDN(I)=0.0
               ER1(I)  =0.0
        IPIS(I)=1
               ER2(I)  =0.0
               ERR1(I) =0.0
               ERR2(I)  =0.0
               SIAE(I)=0.0
               UINT(I)=0.0
               USINT(I)=0.0
               YN(I) =0.0
               UN(I) =0.0
               UNT(I)=0.0
               YSTAR(I)=0.0
               WOLD(I)=0.0
               ACLOSS(I)=0.0
         AKNEW=0.0
         N=0
         IJK=0
         ITEST(I,8)=5
         ITEST(I,1)=1
C
               DO  15 J=1,NPMN
                   P(I,J)=0.0
    15         CONTINUE
C
               DO  20 J=1,NPARN
                   X(I,J)=0.0
                   G(I,J)=0.0
                   DO 20 K=1,11
                      SAVE(I,K,J)=0.0
    20         CONTINUE
   25    CONTINUE
          WRITE(IWIO,800)
C
C------------------------------------------------------------
C-
C-  ASK FOR NO. OF SYSTEM AND INTIAL FREQUENCY OF DUMPING
C-  INFORMATION TO DISK.
C-
C
          READ (IRIO,*) NSYSRD , IDMP , IDPR
          DO  90 IS=1,NSYSRD
C
C------------------------------------------------------------
C-
```

```
C-  READING FROM SECTOR 1 [IS=1] AND 4 [IS=2].
C-
C
           CALL READF(IDCB1,IERR,BUF,80,ILG)
           TS(IS)=BUF(2)
      CALL READF(IDCB1,IERR,BUF,90,IDUM)
           ADCM(IS)=     BUF(40)
           ADCC(IS)=     BUF(41)
C
C
           DACM(IS)=     BUF(42)
           DACC(IS)=     BUF(43)
C
C------------------------------------------------------------
C-
C-  READ FROM SECTOR 2 AND 5.
C-
C
        CALL READF(IDCB1,IERR,BUF,80,ILG)
C
C- NO. OF DELAYS FOR CONTROL, INTERACTIVE AND FEEDFORWARD
C- TERM.
C
      K1(IS) = IFIX(BUF(6))
      K2(IS) = IFIX(BUF(7))
      K3(IS) = IFIX(BUF(8))
C
C-  OBTAIN INITIAL PARAMETER GUESS.
C
           IFLG = 0
           NSELF(IS)=0
           IJ       =0
           DO  45 I=1,5
               IF(I .LT. 5) N(IS,I)=IFIX(BUF(I))
               NSELF(IS)=NSELF(IS)+N(IS,I)
               NLOOP    = N(IS,I)
               IF( NLOOP .EQ. 0)  GO TO  45
                 DO  40  J=1,NLOOP
                     IJ = IJ + 1
                     IK = I*10 + J - 1
                          IF(IK .GT. 40) IK = IK -40
                     PAR(IS,IJ)=BUF(IK)
               IF(I.NE.4 .OR. J.GT.1) GOTO 40
               N(IS,5) = IFIX(BUF(5))
               CALL READF(IDCB1,IERR,BUF,90,IDUM)
               IFLG = 1
   40            CONTINUE
   45      CONTINUE
C
C-  TYPE OF IDENTIFICATION SCHEME.
C
```

```
      IF(IFLG.NE.1) CALL READF(IDCB1,IERR,BUF,90,IDUM)
           ITYID(IS)=IFIX(BUF(20))
           ROW(IS,1)=     BUF(21)
           ROW(IS,2)=     BUF(22)
           ROW(IS,3)=     BUF(26)
           PINT     =     BUF(23)
           PINTI=PINT
C
           IF(ITYID(IS).NE.2) GO TO  50
C
C-  USING SQUARE ROOT ID METHOD.
C
C
C
              PINT=SQRT(PINT)
              ROW(IS,1)=SQRT(ROW(IS,1))
              ROW(IS,2)=SQRT(ROW(IS,2))
              ROW(IS,3)=SQRT(ROW(IS,3))
   50      CONTINUE
           IFP(IS,1)=IFIX(BUF(24))
           IFP(IS,2)=IFIX(BUF(25))
           IF(ITYID(IS) .EQ. 3)   GO TO  60
C
C-  COVARIANCE MATRIX FOR ID TYPE 1,2, & 4.
C
             IJ = 0
             IJP= 1
             NLOOP=NSELF(IS)
             DO  55  I = 1,NLOOP
                 IJ  = IJ + I
                 IF(I.NE.IFP(IS,1).AND.I.NE.IFP(IS,2))
     *                    P(IS,IJ) = PINT
   55        CONTINUE
             GO TO  70
C
C-  COVARIANCE MATRIX INITIALIZATION FOR IDENTIFIATION
C-  METHOD 3.
C
   60      IJ = 1
           NLOOP=NSELF(IS)
           IK   = NLOOP
           DO  65 I=1,NLOOP
               IF(I.NE.IFP(IS,1).AND.I.NE.IFP(IS,2))
     *                                              P(IS,IJ) = PINT
               IJ = IK + 1
               IK = IJ + NLOOP - I - 1
   65      CONTINUE
   70    CONTINUE
C
C-  INFORMATION ON SETPOINT.
C
```

```
          ITYW(IS)=IFIX(BUF(30))
          HW(IS)  =     BUF(31)
          LW(IS)  =IFIX(BUF(32))
          BW(IS)  =     BUF(35)
          AKW(IS) =     BW(IS)
C
C-  INFORMATION ON LOAD.
C
          ITYD(IS)=IFIX(BUF(40))
          HD(IS)  =     BUF(41)
          LD(IS)  =IFIX(BUF(42))
          BD(IS)  =     BUF(45)
C
C------------------------------------------------------------
C-
C-  READING FROM SECTOR 3 [IS=1] AND 6 [IS=2].
C
C
C-
C
         CALL READF(IDCB1,IERR,BUF,80,ILG)
           ITYCT(IS)=IFIX(BUF(1))
           IF(ITYCT(IS) .NE. 3) GO TO  80
              DO  75 II=1,6
                  N(IS,II)=0
                  PAR(IS,II)=0.0
   75         CONTINUE
   80      CONTINUE
C
           UBL(IS)   =     BUF(2)
           UTL(IS)   =     BUF(3)
           IRAMP(IS) =IFIX(BUF(4))
           ACT(IS)   =     BUF(6)
           NQ(IS)    =IFIX(BUF(10))
           NP(IS)    =IFIX(BUF(30))
C
           DO  85 I=1,4
               QD(IS,I)=BUF(I+10)
               QN(IS,I)=BUF(I+14)
               PD(IS,I)=BUF(I+30)
               PN(IS,I)=BUF(I+34)
   85      CONTINUE
C
C-  KP,KI,KD USED FOR PID AND Q-WEIGHTING.
C
      CALL READF(IDCB1,IERR,BUF,90,IDUM)
           AKPS(IS)=BUF(21)
           AKIS(IS)=BUF(22)
           AKDS(IS)=BUF(23)
           AKP(IS)=BUF(24)
           AKI(IS)=BUF(25)
           AKD(IS)=BUF(26)
   90  CONTINUE
C
C-  READ IN PRESENT OUTPUT AND EQUATE USS TO PRESENT OUTPUT.
C
      DO 88  IS = 1,NSYSRD
      IDUM = 13
      IF(IS .EQ. 2) IDUM = 9
      CALL AIRD(5,IDUM,IMEA,IERR)
      USS(IS) = 10. * SQRT(IMEA*ADCM(IS) + ADCC(IS))
      IF(ACT(IS) .LT. 0.)  USS(IS) = 100 - USS(IS)
      UN(IS) = USS(IS)
      UPID(IS) = USS(IS)
 88   CONTINUE
C
C-  CLOSE FILES CONTAINING INITIAL STARTING DATA.
C
       CALL CLOSE(IDCB1,IERR)
C
C
C
C
C-----------------------------------------------------------
C-
C-  ASK FOR NAMES OF TWO FILES WHERE DATA WILL BE DUMPED.
C-  OPEN FILE ACCORDINLY.
C-
C
  91  WRITE(IWIO,820)
      READ(IRIO,825)IFILW,ICR
      CALL OPEN(IDCB1,IERR,IFILW,0,77,ICR,144)
      IF(IERR.LT.0) CALL FMGER(IERR)
      WRITE(IWIO,820)
      READ(IRIO,825)IFILW,ICR
      CALL OPEN(IDCB2,IERR,IFILW,0,77,ICR,144)
      IF(IERR.LT.0) CALL FMGER(IERR)
      IDISK=IDMP
      ICNT=IDISK-1
      DO 94 I=1,56
94    BUF(I)=0.0
      MULT=((IFIX(TS(1)))/NSCAN)
      MULT2 = IFIX(TS(2)/TS(1))
C
C*  IJK = MULT-1  WILL CAUSE EXECUTION OF CONTROL SECTION ON
C*  FIRST SCAN.
C
      IJK=MULT-1
      IJK2 = MULT2 -1
C
C-  ASK FOR DESCRIPTOR FOR EACH DATAFILE.  ONE LINE OF 80
C-  ASCII CHARACTERS CAN BE USED.
```

```
C
      DO 940  IS = 1,NSYSRD
      WRITE(IWIO,932) IS
      READ(IWIO,934) (BUF(I) ,I = 1,20)
          IF(IS .EQ. 2) GOTO 935
          CALL WRITF(IDCB1,IERR,BUF,40)
          GOTO 937
 935       CALL WRITF(IDCB2,IERR,BUF,40)
 937       CONTINUE
 940  CONTINUE
C
 934  FORMAT(20A4)
 932  FORMAT(' ENTER DESCRIPTOR FOR',I3)
C
C*  INITIALIZE THE START TIME
C*  ITM1 IS IN UNITS OF 10*MILLISECOND.
C
      CALL EXEC(11,ITIME)
      ITM1=100*ITIME(2)+ITIME(1)
C
C
C
C*************************************************************
C*
C
C
C*  START OF EACH SCAN
C*
C*************************************************************
C
C
C------------------------------------------------------------
C-
C-  READ STATUS OF REGISTER USING SUBROUTINE RSW.  THE STATUS
C-  WILL BE STORED IN ARRAY KRS.  KRS(1) WILL BE THE
C-  STATUS OF BIT 1 FROM FROM THE LEFT,
C-  I.E. BIT 15 ASINDICATED ON THE SWITCH.
C-  A VALUE OF 1 INDICATES THAT THE SWITCH IS UP, 0 IS FOR DOWN.
C-
C
  95  CONTINUE
C
      CALL EXEC(11,ITIME)
      ITM=100*ITIME(2)+ITIME(1)
       CALL RSW(KRS)
      IF(KRS(15).EQ.1) WRITE(IWIO,1000) ITM,ITM1,IWAIT
 1000 FORMAT(' TIME IS = ',2I8,' IWAIT = ',I4)
C
C- DECIDE WHICH SYSTEM
C
      IS=1
```

```
       IF(KRS(9).EQ.1) IS=2
       IF(KRS(1) .EQ. 1) GO TO 105
       IF(KRS(2) .EQ. 0) GO TO 105
C
C-------------------------------------------------------------
C-
C-  BIT 2 FROM LEFT IS ON, WANT TO PRINT OUT VALUES OF
C-  SPECIFIED CONSTANTS.  (BIT2 FROM LEFT IS BIT 14 ON SWITCH
C-  REGISTER).
C-
C
          ASIG=+1.0
          IF(KRS(5).EQ.1) ASIG=-1.0
          AKNEW=AKNEW+ASIG*(FLOAT(KRS(6))+0.1*FLOAT(KRS(7))+
     &                 0.01*FLOAT(KRS(8)) )
          IF(KRS(4).EQ. 1) AKNEW=0.0
          WRITE(IWIO,600)IS,AKNEW,AKP(IS),AKI(IS),AKD(IS)
     &    ,AKW(IS),AKDN(IS),AKPS(IS),AKIS(IS),AKDS(IS)
          GO TO 110
C
C-------------------------------------------------------------
C-
C-  CONVERT REGISTER READING TO TYPE OF ITEST AND THE NEW
C-  VALUE.
C
C
C-
C
C
C
 105   IF(KRS(1).EQ.0) GO TO 110
       IT = KRS(5)+KRS(4)*2+KRS(3)*4+1
       ITEST(IS,IT)=KRS(8)+KRS(7)*2+KRS(6)*4
       IF(ITEST(IS,1).EQ.7) WRITE(IWIO,815) IDX
C
C-------------------------------------------------------------
C-
C-  CHANGE VALUE OF CONSTANTS TO VALUE STORED IN AKNEW.
C-
C
 110  IF(KRS(10).EQ.1)WRITE(IWIO,610)((ITEST(JJ,J),J=1,8),
     *                                  JJ=1,2)
       IF(ITEST(IS,4) .EQ. 1) AKP(IS) =AKNEW + AKP(IS)
       IF(ITEST(IS,4) .EQ. 2) AKI(IS) =AKNEW + AKI(IS)
       IF(ITEST(IS,4) .EQ. 3) AKD(IS) =AKNEW + AKD(IS)
       IF(ITEST(IS,4) .EQ. 5) AKPS(IS)=AKNEW + AKPS(IS)
       IF(ITEST(IS,4) .EQ. 6) AKIS(IS)=AKNEW + AKIS(IS)
       IF(ITEST(IS,4) .EQ. 7) AKDS(IS)=AKNEW + AKDS(IS)
C
      IF(ITEST(IS,5) .EQ. 1) AKW(IS)=AKNEW
      IF(ITEST(IS,5) .EQ. 2) AKDN(IS)=AKNEW
      IF(ITEST(IS,5) .EQ. 3) TPFIL=AKNEW
      IF(ITEST(IS,5) .EQ. 6) USS(IS)=AKNEW + USS(IS)
      IF(ITEST(IS,5) .EQ. 7) IRAMP(IS)=IFIX(AKNEW)+IRAMP(IS)
      IF(ITEST(IS,6) .EQ. 7) MULT=((IFIX(AKNEW))/NSCAN)
C
C-  CHECK IF JUST WAITING, WANT TO STOP, READ INITIAL DATA
C-  FILE AGAIN.
C
      IF(ITEST(1,8).EQ.5.OR.ITEST(2,8).EQ.5) GOTO 301
      IF(ITEST(IS,8).GE.6) GOTO 999
C
C
C-----------------------------------------------------------
C-
C-  CHECK FOR NEW VALUE OF SETPOINT.
C-
C
       DO  157 IS=1,NSYSRD
         WO(IS)=BW(IS)
         IF(ITEST(IS,2) .EQ. 0) IMW(IS)=0
         IF(ITEST(IS,2) .EQ. 3) WO(IS) =AKW(IS)
         IF(ITEST(IS,2) .EQ. 6) WO(IS) =BW(IS)+11.67
         IF(ITEST(IS,2) .EQ. 7) WO(IS) =BW(IS)-11.67
  140      IF(ITEST(IS,4) .NE. 4)  GO TO 156
C
C-----------------------------------------------------------
C-
C-  RESETTING THE Q-MATRIX
C-
C
                 NQ(IS)=1
                 DO  145 I=1,4
C
C
                     QD(IS,I)=0.0
                     QN(IS,I)=0.0
  145            CONTINUE
C
C-  IF KRS(14) IS UP, THEN WANT TO REMOVE Q-FILTER.
C
      IF(KRS(14).EQ.0) GO TO 147
      QD(IS,1)=1
      GO TO 155
C
C- RESETTING Q-MATRIX TO PID FILTER.
C
 147  NQ(IS)=3
      QN(IS,1)=1.0
      QN(IS,2)=-1.0
          QD(IS,1) = AKP(IS) + AKI(IS) + AKD(IS)
          QD(IS,2) = -(AKP(IS) + 2*AKD(IS))
          QD(IS,3) = AKD(IS)
C
 155       WRITE(IWIO,605)IS,AKP(IS),AKI(IS),AKD(IS)
     &           ,IS,NQ(IS),(QD(IS,J),J=1,4),(QN(IS,J),J=1,4)
  156    CONTINUE
C
C
         IF(ITEST(IS,5).EQ.0) GO TO 157
            IF(ITEST(IS,5).EQ.4) WRITE(IWIO,606)TPFIL
            IF(ITEST(IS,5).NE.5) GO TO 157
C
C------------------------------------------------------------
C-
C-  RESETTING THE P-WEIGHTING.
C-
C
               NP(IS)=1
               PD(IS,1)=1.0
               PN(IS,1)=1.0
               PN(IS,2)=0.0
               IF(TPFIL.LE.0.0)  GO TO 157
                  NP(IS)=2
                  PN(IS,2)=-EXP(-1.0/TPFIL)
                  PD(IS,1)=1.0-PN(IS,2)
           WRITE(IWIO,607)TPFIL,IS,NP(IS),(PN(IS,J),J=1,4),
     &     (PD(IS,J),J=1,4)
157       WN(IS)=WO(IS)
C
C------------------------------------------------------------
C-
C-  RESETTING THE COVARIANCE MATRIX.
C-
C
      IS=1
      IF(KRS(9).EQ.1) IS=2
      IF(ITEST(IS,6).NE.3) GOTO 480
C
C
      PIN=PINTI
      PIN=SQRT((10.0)**(AKNEW))
C
      DO 455 I=1,NPMN
      P(IS,I)=0.0
      IF(I.LE.30) G(IS,I)=0.0
 455  CONTINUE
C
      IJ=0
      NLOOP=NSELF(IS)
      DO 460 I=1,NLOOP
      IJ=IJ+I
      IF(I.NE.IFP(IS,1).AND.I.NE.IFP(IS,2)) P(IS,IJ)=PIN
```

```
C
      WRITE(IWIO,990)IS,I,IJ,P(IS,IJ)
  460 CONTINUE
C
  480 CONTINUE
      IJK=IJK+1
      IF(IJK.LT.MULT) GOTO 301
C
C-----------------------------------------------------------
C-
C-      TIME TO DO CONTROL CALCULATION.
C-      NOTE, HAVE TO CHECK IF DOING BOTH SYSTEM OR JUST ONE
C-      FOR CASE WHERE 2 SYSTEM HAVE DIFFERENT SAMPLE RATE.
C-     SECOND MUST BE A MULTIPLE OF FIRST.
C-
C
   97 IJK2=IJK2+1
      NSYS=NSYSRD
      IF(IJK2.LT.MULT2) NSYS = 1
      IF(IJK2 .GE. MULT2) IPIS(2)=IPIS(2)+1
      IF(IJK2. GE. MULT2) IJK2 = 0
      IJK=0
      M=M+1
      IF(M.GT.9999) M=1
       IPIS(1) = IPIS(1) + 1
       IF(  IPIS(1) .GT. 30  )    IPIS(1) = 1
      IF(  IPIS(2) .GT. 30  )   IPIS(2) = 1
C
C-  GET INPUT MEASUREMENT.
C-  READING IN 5 POINTS, THEY ARE:
C-      POINT NO.      DESCRIPTION
C-         15       TOP COMPOSITION
C-         10       DISTILLATE FLOW
C-         13       REFLUX FLOW
C-          9       STEAM FLOW
C-         12       FEED
C
      CALL AIRD(5,ICX,IDX,IERR)
      DO 96 KJI=1,5
      SADC(KJI)=FLOAT(IDX(KJI))
C
C
 96   CONTINUE
      YBTM=FLOAT(ICOM(ICOM(8)+1))*0.001
      YTOP=ADCM(1)*SADC(1)+ADCC(1)
      YN(1)=YTOP
      YN(2)=YBTM
      IDX(6)=YBTM
C
      FEED    = ADCM(1) * SADC(5)  +  ADCC(1)
      DIST    = ADCM(1) * SADC(2)  +  ADCC(1)
      UDIS(1) = ADCM(1) * SADC(3)  +  ADCC(1)
      UDIS(2) = ADCM(1) * SADC(4)  +  ADCC(1)
C
C--------------------------------------------------------------
C-
C-  FILTERING OF Y USING THE P-WEIGHT.
C-  SWITCH 3 UP THEN WANT TO ADD DISTURBANCE INCREMENTALLY.
C-
C
       DO  159 IS=1,NSYS
      IP=IPIS(IS)
           DN(IS) = 0.0
           IF(ITEST(IS,3) .EQ. 4) DN(IS)=FEED-BD(IS)*KRS(13)
           DPR(IS)=(YN(IS)-YSTAR(IS))*IDPR
           SAVE(IS,1,IP)=0.0
           SAVE(IS,3,IP)=DN(IS)
           SAVE(IS,4,IP)=WN(IS)
           SAVE(IS,6,IP)=YN(IS)
           SAVE(IS,7,IP)=DPR(IS)
  159  CONTINUE
C
C
       DO  240 IS=1,NSYS
      IP=IPIS(IS)
           YPD = YN(IS)
           NLOOP=NP(IS)
           IF(NLOOP .LT. 2 ) GO TO 165
C
C-  YD = 1 / PD(Z)  *  YN
C
           DO  160 J=2,NLOOP
               IC=IP-J+1
               IF(IC .LT. 1)  IC=IC+30
               YPD = YPD - PD(IS,J)*SAVE(IS,2,IC)
  160      CONTINUE
           IF(PD(IS,1).LE.0.0) WRITE(IWIO,700)
           IF(PD(IS,1).LE.0.0) PD(IS,1)=1.0
  165      YPD = YPD/PD(IS,1)
           SAVE(IS,2,IP)=YPD
C
C-  YP = PN(Z) / PD(Z)  *  YN
C
           YP = 0.0
           SAVE(IS,8,IP)=0.0
C
C
           NLOOP=NP(IS)
           DO  170 J=1,NLOOP
               IC=IP-J+1
               IF(IC .LT. 1) IC=IC+30
               YP = YP + PN(IS,J)*SAVE(IS,6,IC)
               YP = YP - PD(IS,J)*SAVE(IS,8,IC)
  170      CONTINUE
           YP = YP/PD(IS,1)
           SAVE(IS,8,IP)=YP
C
C------------------------------------------------------------
C-
C-  ACCUMULATE COST FUNCTION AND ERROR.
C-
C
           IC = IP - K1(IS) - 1
           IF(IC .LT. 1)  IC=IC + 30
           PHI(IS)= YP - SAVE(IS,4,IC) + SAVE(IS,9,IC)
           ACLOSS(IS)=ACLOSS(IS) + PHI(IS)*PHI(IS)
           YERR(IS)=YN(IS) - YSTAR(IS)
C
C------------------------------------------------------------
C-
C-  CHECK WHICH IDENTIFICATION ALGORITHM.  AT PRESENT ONLY
C-  LEAST SQUARE USING LEAST SQUARE ROOT.
C-
C
      IF(ITEST(IS,6) .EQ. 1) GO TO 200
      CALL IDENT2(PHI(IS),NSELF(IS),IS,PERERR(IS)
     *             ,X,PAR,P,G,ROW,IFP)
  200 CONTINUE
C
C------------------------------------------------------------
C-
C-  CALCULATING YSTAR AND X*THETA LESS THAT CONTRIBUTION OF THE
C-  CONTROL ACTION IN THIS SCAN.
C-
C
           IJ = 0
           XP = 0.0
           YSTAR(IS)=0.0
C
           DO  220 I=1,5
               NLOOP = N(IS,I)
               IF(NLOOP .EQ. 0)    GO TO 220
                 K=0
                 ISTMP=IS
                 ITEMP = I
                 IF(I .EQ. 3) K=K3(IS)
                 IF(I.EQ.3 .AND.IDPR.EQ.1) ITEMP=7
                 IF(I .NE. 5) GO TO 205
                   ISTMP = 2
                   IF(IS .EQ. 2)  ISTMP = 1
C
C
                   ITEMP  = 1
```

```
                  K = K2(IS)
 205              DO  215 J=1,NLOOP
                      IJ = IJ + 1
                      IC = IP - J + 1 - K
                      IF(IC .LT. 1) IC=IC+30
                      XP=XP+PAR(IS,IJ)*SAVE(ISTMP,ITEMP,IC)
                      IF(I.EQ.4) GO TO 210
                      YSTAR(IS)=YSTAR(IS) +
     &                     PAR(IS,IJ)*SAVE(ISTMP,ITEMP,IC)
 210                IC = IC - K1(IS)
                    IF( IC .LT. 1) IC = IC + 30
                    X(IS,IJ)=SAVE(ISTMP,ITEMP,IC)
 215            CONTINUE
 220       CONTINUE
C
C- CHECK TYPE OF VALVE ACTION.
C
      IF(ITEST(IS,6).EQ.5) ACT(IS)=-ACT(IS)
          IF(ITYCT(IS) .NE. 3) GO TO 225
                XP =(YN(IS) - WN(IS)) * ABS(ACT(IS))/ACT(IS)
 225      CONTINUE
C
C------------------------------------------------------------
C-
C-  CALCULATING NEW CONTROL ACTION.
C-
C-
          SAVE(IS,10,IP)=XP
          CO(IS)=0.0
          CA(IS)=QN(IS,1) + PAR(IS,1)*QD(IS,1)
          CB(IS)=0.0
          NLOOP=NQ(IS)
C
          DO  230 J=1,NLOOP
              IC=IP-J+1
              IF( IC .LT. 1 )   IC=IC+30
              CO(IS)=CO(IS)-QD(IS,J)*SAVE(IS,10,IC)
              CO(IS)=CO(IS)-(QN(IS,J)+PAR(IS,1)*QD(IS,J))
      *                      *SAVE(IS,1,IC)
 230      CONTINUE
C
C
          IF(N(IS,5) .EQ. 0)  GO TO 240
              NS=NSELF(IS)-N(IS,5)+1
              NLOOP=NQ(IS)
              CB(IS)=PAR(IS,NS)*QD(IS,1)
              IJ=NS
C
              DO  235 J=1,NLOOP
                  ISTMP=2
                  IF(IS .EQ. 2) ISTMP=1
```

```
             IC=IP - J + 1
C
C
             IF(IC .LT. 1) IC=IC+30
             CO(IS)=CO(IS)-PAR(IS,NS)*QD(IS,J)
                      *SAVE(ISTMP,1,IC)
 235         CONTINUE
 240    CONTINUE
      DEN = CB(1)*CB(2) -CA(1)*CA(2)
      IF(DEN .EQ. 0.0) WRITE(IWIO,705)
      IF(DEN .EQ. 0.0) DEN =1.0
      UNT(1)=(CO(2)*CB(1)-CO(1)*CA(2))/DEN
      UNT(2)=(CO(1)*CB(2)-CO(2)*CA(1))/DEN
C
C------------------------------------------------------------
C-
C-  OBTAIN INDEX IP1 AND IP2 FOR PREVIOUS AND PREVIOUS,
C-  PREVIOUS VALUE IN SAVE VECTOR.
C-
C
     DO 241 IS=1,NSYS
     IP=IPIS(IS)
     IP1(IS)=IP-1
     IF(IP1(IS).LT.1) IP1(IS)=30
     IP2(IS)=IP1(IS)-1
     IF(IP2(IS).LT.1) IP2(IS)=30
241  CONTINUE
C
C------------------------------------------------------------
C-
C-   CALCULATING PID CONTROL ACTION.
C-
C
     DO  250  IS=1,NSYS
    IP=IPIS(IS)
       PCNT=(UTL(IS)-UBL(IS))*IRAMP(IS)/100.0
       UTOP    =UN(IS)+PCNT
       UBOT    =UN(IS)-PCNT
       ERR2(IS)= ERR1(IS)
       ERR1(IS)= ER1(IS)
       ER1(IS) = UN(IS) - YN(IS)
C
C- UPDATING SIAE COUNTER.
C
    IF(ITEST(IS,6).EQ.6) SIAE(IS)=0.0
       SIAE(IS)= SIAE(IS) + ABS(ER1(IS))
       UPROP(IS)=AKPS(IS)*ER1(IS)
       IF(ITEST(IS,8).LE.2) GOTO 247
       IF(ITEST(IS,8).EQ.4.AND.AKIS(IS).NE.0.0) GOTO 247
       IF(ITEST(IS,8).EQ.4) GOTO 248
C
```

```
           UDER(IS)=AKDS(IS)*(ERR1(IS)-ER1(IS))
           UINT(IS)=UINT(IS)+AKIS(IS)*ER1(IS)
           UPID(IS)=UPROP(IS)+UINT(IS)+UDER(IS)
           GOTO 246
C
C
C
 247       UINT(IS)=UN(IS)-UPROP(IS)
           IF(ITEST(IS,8).EQ.4) GOTO 248
C
C------------------------------------------------------------
C-
C-  INCREMENTAL CONTROL EQUATION
C-
C
 245       UPROP(IS)= ER1(IS)-ERR1(IS)
      ID1=IP1(IS)
      ID2=IP2(IS)
           UDER(IS)=AKDS(IS)*(YN(IS)-2.*SAVE(IS,6,ID1)
     *                             +SAVE(IS,6,ID2))
           UDINT(IS)=AKIS(IS)*ER1(IS)
           USINT(IS)=USINT(IS)+UDINT(IS)
           DELTA=UPROP(IS)+UDINT(IS)+UDER(IS)
           UPID(IS)=UPID(IS)+DELTA*AKPS(IS)
      IF(ITEST(IS,8) .EQ. 4) UPID(IS) = USS(IS)
C
 246       IF(ITEST(IS,8).EQ.0) UN(IS)=UPID(IS)
           IF(ITEST(IS,8).EQ.3) UN(IS)=UPID(IS)
           IF(ITEST(IS,8).NE.0.AND.ITEST(IS,8).NE.3)
     *                                   UPID(IS) = UN(IS)
           IF(ITEST(IS,8).EQ.2) UN(IS)=UNT(IS)+USINT(IS)
           IF(ITEST(IS,8).EQ.1) UN(IS)=UNT(IS)
 248       IF(ITEST(IS,8).EQ.4) UN(IS)=USS(IS)
C
C------------------------------------------------------------
C-
C-  LIMIT CHECKING.
C-
C
      IF(ITEST(IS,1) .GE. 1) WRITE(IWIO,630) UN(IS)
           IF(UN(IS) .GT. UTOP     ) UN(IS)=UTOP
      IF(UPID(IS) .GT. UTOP    ) UPID(IS)=UTOP
           IF(UN(IS) .LT. UBOT     ) UN(IS)=UBOT
      IF(UPID(IS) .LT. UBOT    ) UPID(IS)=UBOT
C
C-  CHECK RESET WINDUP.
C
      IF(UN(IS).LT.UTL(IS)) GOTO 249
      UINT(IS)=UINT(IS)+(UN(IS)-UTL(IS))
      USINT(IS)=USINT(IS)+(UN(IS)-UTL(IS))
      UN(IS)=UTL(IS)
```

```
  249 IF(UN(IS).GT.UBL(IS)) GOTO 942
      UINT(IS)=UINT(IS)+(UN(IS)-UBL(IS))
      USINT(IS)=USINT(IS)+(UN(IS)-UBL(IS))
      UN(IS)=UBL(IS)
  942 CONTINUE
C
C------------------------------------------------------------
C-
C-  CALCULATING THE NEW YSTAR  I.E. ESTIMATE OF Y
C
C
C-
           ISTMP = 2
           IF(IS .EQ. 2) ISTMP = 1
           NS = NSELF(IS) - N(IS,5) + 1
           YSTAR(IS)=YSTAR(IS)+PAR(IS,1)*UN(IS)
     *                           +PAR(IS,NS)*UN(ISTMP)
           SAVE(IS,1,IP)=UN(IS)
C
C-  IF SWITCH 3 IS UP, WANT TO IDENTIFY ONLY.  READ IN THE
C-  CONTROL
C
      IF(KRS(14).EQ.1)  SAVE(IS,1,IP) = UDIS(IS)
           IC=IP-K1(IS)
           IF(IC .LT. 1) IC=IC+30
           X(IS,1)=SAVE(IS,1,IC)
  250    CONTINUE
C
C------------------------------------------------------------
C-
C-  SENDING OUTPUT
C-
C
C
      DO 251 IS=1,NSYS
           USEND(IS) = UN(IS)
           IF(ACT(IS) .LT. 0) USEND(IS) = ABS(ACT(IS))-UN(IS)
           USEND(IS) = USEND(IS)**2 * DACN(IS) + DACC(IS)
           IOUT = IFIX(USEND(IS))
           IF(KRS(16) .EQ. 1) CALL OUT(IOUTCH(IS),IOUT,IERR)
      IF(KRS(16).EQ.0) WRITE(IWIO,1234)
 1234 FORMAT(' NOT SENDING OUTPUT')
  251 CONTINUE
C
C************************************************************
C*
C*  SECTION TO PRINT OUT THE RESULTS.
C*
C************************************************************
C
         DO 299 IS=1,NSYS
      IP=IPIS(IS)
          ICH=ITEST(IS,8)+1
          IF(ITEST(IS,1).EQ.0) GO TO 274
          IF(ITEST(IS,1).LT.5)
     *                         WRITE(IWIO,615) CHAR(ICH),IS,
     *                   M,WN(IS),YN(IS),YSTAR(IS),DN(IS),
     *                   UN(IS),USEND(IS),PHI(IS),SIAE(IS)
C
  272     IF(ITEST(IS,1).LT.3 .OR. ITEST(IS,1).GT.4) GO TO 273
          NPAR=NSELF(IS)
          WRITE(IWIO,625)(IS,J,PAR(IS,J),G(IS,J),J=1,NPAR)
C
  273     IF(ITEST(IS,1).EQ.4)
C
C
     *                         CALL PWRITE(ITYID(IS),
     *       NSELF(IS),IS,IWIO,1,X,PAR,P,G,ROW,IFP)
  274     CONTINUE
C
C-------------------------------------------------------------
C-
C- UPDATE THE MEASUREMENT VECTOR, I.E. ADD EFFECT OF SETPOINT
C- AND INTERACTIVE TERMS.
C-
C
            IF(N(IS,5).EQ.0) GO TO 255
                 NS=NSELF(IS)-N(IS,5)+1
                 IC=IP-K2(IS)-K1(IS)
                 IF(IC.LT.1) IC=IC+30
                 ISTMP=2
                 IF(IS.EQ.2)ISTMP=1
                 X(IS,NS)=SAVE(ISTMP,1,IC)
  255       CONTINUE
C
C-------------------------------------------------------------
C-
C-  CALCULATED Q-FILTERED VALUE OF U(T).
C-
C
           UQ = 0.0
           NLOOP=NQ(IS)
           SAVE(IS,9,IP)=0.0
           IF(ITYCT(IS) .EQ. 3)    GO TO 265
              DO  260 J=1,NLOOP
                   IC=IP-J+1
                   IF(IC .LT. 1)   IC = IC + 30
                   UQ = UQ - QD(IS,J)*SAVE(IS,9,IC)
                   UQ = UQ + QN(IS,J)*SAVE(IS,1,IC)
  260         CONTINUE
  265       IF(QD(IS,1).EQ.0.0) WRITE(IWIO,710)
            IF(QD(IS,1).EQ.0.0) QD(IS,1)=1.0
```

```
             SAVE(IS,9,IP)=UQ/QD(IS,1)
C
C*  ESTIMATING W-OLD
C
  297    IC = IP -K1(IS)
         IF(IC .LT. 1) IC=IC+30
         WOLD(IS) = SAVE(IS,4,IC)
         NS = NSELF(IS)  -  N(IS,5) - N(IS,4) + 1
         NF = NSELF(IS) -  N(IS,5)
C        IF(ITYCT(IS) .EQ. 1)  GO TO 290
         IF(ITYCT(IS) .EQ. 3)  GO TO 290
              DO 298 I=NS,NF
                   IC=IP - I - K1(IS) + NS
                   IF(IC .LT. 1) IC=IC+30
                   X(IS,I)=X(IS,I) - SAVE(IS,9,IC)
  298        CONTINUE
  290    CONTINUE
C
C
  299 CONTINUE
C
C
C------------------------------------------------------------
C-
C-  CHECK IF IT IS TIME TO STORE INFORMATION TO DISK.
C-
      ICNT=ICNT+1
      IF(ICNT.LT.IDISK) GOTO 301
C
C------------------------------------------------------------
C-
C-  TRANSFER INFORMATION TO DISK.
C-
C
      ICNT=0
      IDISK=IDMP
C
      DO 305 IS=1,NSYS
      IF(ITEST(IS,7).EQ.4) GOTO 999
      IF(ITEST(IS,7).EQ.7) IDMP=IFIX(AKW(IS))
      IF(ITEST(IS,7).LE.1) GOTO 307
      BUF(1)=FLOAT(ICH)
      BUF(2)=FLOAT(IS)
      BUF(3)=FLOAT(M)
      BUF(4)=WN(IS)
      BUF(5)=YN(IS)
      BUF(6)=UN(IS)
      BUF(7)=PHI(IS)
      BUF(8)=SIAE(IS)
      BUF(9)=YTOP
      BUF(10)=UDIS(1)
      BUF(11)=YBTM
      BUF(12)=FEED
      BUF(13)=UDIS(2)
      BUF(14)=DIST
      BUF(15)=YSTAR(1)
      BUF(16)=YSTAR(2)
C
C-----------------------------------------------------------
C-
C-  BUF(15) ---- BUF(85)
C-
C
C
      NPAR=NSELF(IS)
      NPTS = 2 * (16 + 2*NPAR)
      DO 302 I=1,NPAR
  302 BUF(16+I)=PAR(IS,I)
C
      DO 303 I=1,NPAR
  303 BUF(16+NPAR+I)=G(IS,I)
C
C
C
C
C     IF(NPAR.GE.10) GOTO 308
C     NPE=(NPAR**2+NPAR)/2
C     DO 304 I=1,NPE
C304  BUF(14+2*NPAR+I)=P(IS,I)
C
  308 IF(IS.EQ.2) GOTO 306
      CALL WRITF(IDCB1,IERR,BUF,NPTS)
      GOTO 307
  306 CALL WRITF(IDCB2,IERR,BUF,NPTS)
  307 CONTINUE
C
  305 CONTINUE
C
C*  CALL TIME TO CHECK HOW LONG PROGRAM SHOULD BE SUSPENDED
C*  BEFORE NEXT SCAN.  NOTE, EXCEPT FOR INITIAL SCAN, THE
C*  START TIME OF THE NEXT SCAN IS CALCULATED FROM END OF
C*  THIS SCAN + TIME IN WAIT.  IF THE PROGRAM BECOMES
C*  SUSPENDED FOR LONGER THAN SPECIFIED TIME (DUE TO LOAD-
C*  ING) THE NEXT SUSPEND WILL BE SHORTENED.
C
  301 CONTINUE
      CALL EXEC(11,ITIME)
      ITM2=100*ITIME(2)+ITIME(1)
      IDIF=ITM2-ITM1
  312 IF(IDIF.GE.0) GO TO 315
      IDIF=IDIF+6000
      GO TO 312
```

```
C
C*  CHECK IF CONTROL CALCULATION WITHIN THE SCAN TIME.
C
  315 IF(IDIF.LE.ISCAN) GO TO 320
      WRITE(IWIO,900) IDIF
      IDIF=IDIF-ISCAN
      ITM1=ITM1+ISCAN
      IJK=IJK+1
      IF(IJK.GE.MULT) GO TO 97
      GO TO 315
C
  320 IWAIT=ISCAN-IDIF
      ITM1=ITM2+IWAIT
      CALL WAIT(IWAIT,0,IERR)
      GO TO 95
C
C---------------------------------------------------------------
C-
C-  CLOSE FILES AND EXIT
C-
C
  999 CALL CLOSE(IDCB1,IERR)
      CALL CLOSE(IDCB2,IERR)
C
      IF(ITEST(IS,8) .EQ. 6) GO TO 5
C
C
      IF(ITEST(IS,7) .EQ. 4) GO TO 91
      STOP
C
C***************************************************************
C*
C*  FORMAT STATEMENTS
C*
C***************************************************************
C
  600 FORMAT(' AK-',I1,'=',G12.5,' P',F8.2,' I',F8.2,
     &' D',F8.2,' W',F8.2       ,' D',F8.2,/,
     &       ' PID =',F8.2,' I',F8.2,' D',F8.2)
  605 FORMAT(' RESET Q-FILTER  IS=',I1,/,
     &       1X,' AKP=',F8.3,' AKI=',F8.3,' AKD=',F8.3,/,
     &       ' QD(',I1,',',I1,')=',G12.5,1X,G12.5,1X,G12.5,1X,
     &G12.5,/,' QN(-,-)=',G12.5,1X,G12.5,1X,G12.5,1X,G12.5,1X)
  606 FORMAT(' T-P-FILTER =',G12.5)
  607 FORMAT(' RESET P-FILTER  T-P=',G12.5,/,
     &       ' PD(',I1,',',I1,')=',G12.5,1X,G12.5,1X,G12.5,1X,
     &G12.5,/,'PN(-,-)=',G12.5,1X,G12.5,1X,G12.5,1X,G12.5)
  610 FORMAT(' ITEST=',8(I2,1X),5X,8(I2,1X) )
  615 FORMAT(10X,'ITR',2X,'SETPT',2X,'MEAS.',3X,'YSTAR',5X,
     *'DN',6X,'UN',5X,'OUT',6X,,'PHI',5X,'SIAE',/,
     *       1X,A4,'M-',I1,'=',I5,1X,F5.2,1X,F7.3,1X,F7.3,1X,
      &F7.2,1X,F7.3,1X,F7.1,1X,G8.3,1X,G8.3)
  625 FORMAT(1X,'PAR(',I1,',',I3,')=',G12.5,'  K-G=',G12.5)
  630 FORMAT(1X,'CAL. OUTPUT = ',G10.5)
  700 FORMAT('  PD IS ZERO, RESET TO 1.0 ')
  705 FORMAT(' CA IS ZERO, RESET TO 1.0 ')
  710 FORMAT(' QD IS ZERO, RESET TO 1.0 ')
800   FORMAT(2X,'ENTER NSYS,IDMP,IDPR: ','_')
  805 FORMAT(2I7)
  810 FORMAT(1X,5(G12.5,1X))
815   FORMAT(1X,'TP-PR ',F7.2,' DS-FL ',F7.2,' RF-FL ',F7.2,
     &      'ST-FL ', F7.2,' FE-FL ',F7.2,' BT-PR ',F7.2)
  820 FORMAT(2X,'INPUT DATA DUMP FILES.......MUST EXIST',
     *           ' ALREADY',/,
     &       2X,'ITEST(7) MUST BE 2 TO DUMP !!!!')
  825 FORMAT(3A2,I3)
  900 FORMAT(2X,' EXCEED TIME SCAN, TIME NEEDED = ',I10)
  990 FORMAT(' IS=',I2,' LOOP=',I7,' P(',I4,')=',G12.5)
      END
:
```

```
FTN4
      SUBROUTINE ZTRAN(ITYP,TS,GAIN,T,A,B,NA,NB)
      DIMENSION T(3),A(20),B(20)
      DO  10 I=1,20
         A(I)=0.0
         B(I)=0.0
   10 CONTINUE
      NA=1
      NB=1
      A(1)=1.0
      B(1)=0.0
      IF(ITYP .LE. 0 .OR. ITYP .GT. 5) GO TO 40
      GO TO( 15 , 20 , 25 , 30 , 35) , ITYP
CC        FIRST ORDER LAG     1/(TS+1) ..............
C
   15  NB=1
       NA=2
       B(1)=GAIN*(1.0-EXP(-TS/T(1) ) )
       A(2)=-EXP(-TS/T(1))
       GO TO 40
C
C      SECOND ORDER  1/(S)(S+1)...............
C
   20  NB=2
       NA=3
       B(1)=GAIN*(TS-T(1)*(1.-EXP(-TS/T(1)) ) )
       B(2)=GAIN*( -EXP(-TS/T(1))*TS + T(1)*(1.-EXP(-TS/T(1)) )
       A(2)=-(1.0+EXP(-TS/T(1)))
       A(3)=-EXP(-TS/T(1))
       GO TO 40
C
C      SECOND ORDER  1/(ST1+1)(ST2+1)
C
   25  AA=EXP(-TS/T(1))
       BB=EXP(-TS/T(2))
       NB=2
       NA=3
       B(1)=GAIN*( (BB/T(2)-AA/T(1))/(1./T(2)-1./T(1))-(AA+BB)+1
       B(2)=GAIN*(AA*BB-(BB/T(2)-AA/T(1))/(1./T(2)-1./T(1)) )
       A(2)=-(BB+AA)
       A(3)=AA*BB
       GO TO 40
C
C      SECOND ORDER    1/(TS + 1)(TS + 1)
C
   30  NB=2
       NA=3
       AA=EXP(-TS/T(1))
       B(1)=GAIN*( -(1.+TS/T(1))*AA+1.0)
       B(2)=GAIN*(AA*AA - (1. - TS/T(1))*AA)
       A(2)=-2.*AA
```

```
        A(3)=AA*AA
        GO TO 40
C
C       SECOND ORDER    1/(T1S*S + T2S + 1)........
C
  35     AA = T(2)/(2.*T(1))
         BB = 1/T(1) - (T(2)*T(2))/(T(1)*2.)**2
         IF(BB.LT.0.0) GO TO 40
            BB=SQRT(BB)
            B(1)=EXP(-AA*TS)*(-COS(BB*TS)-AA/BB*SIN(BB*TS))+1.0
            B(2)=EXP(-2.*AA*TS)-EXP(-AA*TS)*(COS(BB*TS)-AA
    &            /BB*SIN(BB*TS))
            A(1)=1.0
            A(2)=-2.*EXP(-AA*TS)*COS(BB*TS)
            A(3)=EXP(-2.*AA*TS)
            A(3)=EXP(-2.*AA*TS)
            B(1)=GAIN*B(1)/(T(1)*(BB*BB+AA*AA))
            B(2)=GAIN*B(2)/(T(1)*(BB*BB+AA*AA))
            NB=2
            NA=3
  40 RETURN
     END
:
```

```
      SUBROUTINE RSW(IRSW)
      DIMENSION IRSW(16)
      CALL DI(1,1,ID,IERR)
      IRSW(16)=0
      IF(ID .LT. 0) IRSW(16)=1
      IF(ID .LT. 0) ID = ID + 32766 + 2
      IF(IERR .NE. 1) GO TO 999
      DO 100 I = 2,16
        IJ = 16 - I
        IRSW(IJ+1)=0
        IDT = ID / (2**IJ)
        IF(IDT .EQ. 1) IRSW(IJ+1)=1
        IF(IDT .EQ. 1) ID = ID - 2**IJ
100    CONTINUE
      DO 200 I = 1,8
         ITEMP      =    IRSW(17-I)
         IRSW(17-I)=    IRSW(I)
         IRSW(I)    =    ITEMP
200   CONTINUE
999   RETURN
      END
      SUBROUTINE IDENT2(YNEW,N,IS,PERER,X,A,P,G,ROW,IFP)
      DIMENSION X(2,30),A(2,30),P(2,465),G(2,30),ROW(2,3),IFP(2,2)
C
C..............................................................
C
C
C      RECURSIVE SQUARE ROOT ALGORITH.....
C
C
C..............................................................
C
      PERER = YNEW
      DO  10 I=1,N
          PERER = PERER - X(IS,I)*A(IS,I)
   10 CONTINUE
C
      GAMA = ROW(IS,1)
      GAMA2= ROW(IS,1)*ROW(IS,1)
      IJ=0
      JI=0
      DO  30 J=1,N
          PX = 0.0
          J1 = J - 1
          DO  15 I=1,J
              JI = JI + 1
              PX = PX + P(IS,JI)*X(IS,I)
   15     CONTINUE
          ALFA  = GAMA/ROW(IS,2)
          BETA  = PX/GAMA2
          GAMA2 = GAMA2 + PX*PX
          GAMA  = SQRT(GAMA2)
          ALFA  = ALFA/GAMA
          G(IS,J)  = P(IS,JI)*PX
          P(IS,JI) = ALFA*P(IS,JI)
          IF(J1 .EQ. 0) GO TO  25
             DO  20 I=1,J1
                IJ = IJ + 1
                PQP = P(IS,IJ)
                P(IS,IJ)=ALFA*(PQP-BETA*G(IS,I) )
                G(IS,I)=G(IS,I) + PQP*PX
   20        CONTINUE
   25    CONTINUE
         IJ = IJ + 1
   30 CONTINUE
C
      PERER = PERER
      DO  35 I=1,N
        G(IS,I)=G(IS,I)/GAMA2
         A(IS,I) = A(IS,I)  + G(IS,I)*PERER
   35 CONTINUE
C
      RETURN
      END
      SUBROUTINE PWRITE(ITYPE,N,IS,IWIO,IPRNT,X,A,P,G,ROW,IFP)
      DIMENSION D(30) , CHAR(5)
      DIMENSION X(2,30),A(2,30),P(2,465),G(2,30),ROW(2,3),IFP(2,2)
C................................................................
C
C         PRINTING ROUTINE ......
C
C
C
C......................................................................
C
C
      DATA CHAR/4HRLS ,4HRSR ,4HUDU ,4HRL  ,4H+---/
       JS = 0
       IF(ITYPE.LT.1 .OR. ITYPE .GT. 3) GO TO  65
       IF(IPRNT.EQ.1) WRITE(IWIO,70)CHAR(ITYPE)
       DO  60 I=1,N
           DO  10 L=1,N
   10      D(L)=0.0
           GO TO ( 15 , 25 , 40 , 65),ITYPE
C
C---------- RLS -------------------------------
C
   15      DO  20 J=I,N
              IJ= J*(J-1)/2 + I
              IF(J .LT. I)    IJ= I*(I-1)/2 + J
              D(J-I+1)=P(IS,IJ)
   20      CONTINUE
           GO TO  55
C
C----------RSR -----------------------
C
   25      DO  35 J=I,N
               KDO = N - J + 1
               J1  = J
               DO  30 K=1,KDO
                    J2 = J1*(J1-1)/2 + I
                    J3 = J1*(J1-1)/2 + J
                    D(J-I+1)=D(J-I+1) + P(IS,J2)*P(IS,J3)
                    J1=J1+1
   30         CONTINUE
   35      CONTINUE
           GO TO  55
C
C---------- U - D - U --------------------------------------
C
   40      J3 = JS
           JDO= N - I + 1
           DO  50 J=1,JDO
               D(J)=0.0
              SUM =1.0
              KDO = JDO - J + 1
              DO  45 K=1,KDO
                  J1 = JS + (J-1) + K
                  J3 = J3 + 1
                  J2 = J2 + KDO - K + 2
                  IF(K .EQ. 1) J2 = J3
                  IF(J.GT.1) SUM = SUM * P(IS,J1)
                  IF(K.GT.1) SUM = SUM * P(IS,J3)
                  SUM = SUM * P(IS,J2)
                  D(J)= D(J)+SUM
   45          CONTINUE
   50       CONTINUE
            JS = J1
C
C
C--------- PRINT SECTION ----------------------
C
   55       ND= N - I + 1
            WRITE(IWIO, 80)ND,(D(L),L=1,ND)
            IF(ND.GT.5)ND=5
            IF(IPRNT.EQ.1)  WRITE(IWIO, 75)(CHAR(5),L=1,ND)
   60   CONTINUE
   65   RETURN
   70   FORMAT(' +-',A4,'-+- DIAGNAL --+',/,
     &        ' +------+','------------+')
   75   FORMAT(' +------',5(A4,9H---------  ))
   80   FORMAT(' I P',I3,' I',20(G12.5,'I',G12.5,'I',G12.5,'I',
     &          G12.5,'I',G12.5,'I',/,' I CONT I') )
        END
:
```

```
FTN4
      PROGRAM HSET () , THIS PROGRAMME GENERATES SELF-TUNER DATAFI
      DIMENSION D(6,85) , N(10) , AIN(10) ,RTYPE(6)
      DIMENSION IDCB(144) , BUF(45) , IFILE(3)
       DIMENSION PRIDNT(5),PRITYP(3)
       DIMENSION T(3) , A(20) , B(20)
       DATA PRIDNT/4HNONE,4HRLS ,4HRSR ,4HU-D ,4HRL  /
       DATA RTYPE/4HTOP ,4HTOP ,4HTOP ,4HBOT ,4HBOT ,4HBOT /
       DATA PRITYP/4HST  ,4HSTPI,4HPID /
       DATA KC,KM,KS,KR/1HC,1HM,1HS,1HR/
      DATA KTWO/1H2/
      DATA ILP/2HLP/
C
C
      DATA ILEN,IFILE/170,2H&H,2HDA,2HTA/
C
C      ...< I/O ROUTINE >..............
C
      IW=LOGLU(IDUMMY)
      IR=IW
      CALL OPEN(IDCB,IERR,IFILE,0,77,136,144)
      IF(IERR .GE. 0) GO TO 5
      CALL FMGER(IERR)
      STOP 4
C
C
 5    WRITE(IW,320)
      READ(IW,*) IFLG
 320  FORMAT(' ENTER 1 IF INITIALIZING FILE: ','_')
      IF(IFLG.EQ.1) GO TO 15
        DO 10 J=1,6
      CALL READF(IDCB,IERR,BUF,80,ILEN)
      IF(IERR .GE. 0) GO TO 6
      CALL FMGER(IERR)
      STOP 4
    6  DO 800  JJ = 1,40
           D(J,JJ) = BUF(JJ)
 800   CONTINUE
C
       CALL READF(IDCB,IERR,BUF,90,ILEN)
       DO 802  JJ = 41,85
       IDUM = JJ - 40
       D(J,JJ) = BUF(IDUM)
802    CONTINUE
    10 CONTINUE
    15 WRITE(IW,125)
       IG=0
       READ (IR,310)ICHAR,ICHARS,ILOG
       IF(ICHARS.EQ.KTWO) IG=1
       IF(ICHAR .EQ. KR  )      GO TO 90
       IF(ICHAR.EQ.KC    .OR.ICHAR.EQ.KM    .OR.ICHAR.EQ.KS    )
```

```
     * GO TO 20
       GO TO 15
   20  ISYS=1 + IG*3
       IF(ICHAR .EQ. KS    )   GO TO 35
       IF(ICHAR .EQ. KC    )   GO TO 45
C
C......MODEL SECTION.................
C
      IF(ILOG.EQ.ILP) IW=6
       NTYPE=IFIX(D(ISYS,1))
      WRITE(IW,1500) RTYPE(ISYS)
       WRITE(IW,150)NTYPE
       IF(NTYPE .GT. 0) GO TO 25
C
C......... Z - TRANSFER MODEL SIMULATION ...............
C
           NF =IFIX(D(ISYS,10))
           NFP=NF+11
           WRITE(IW,155)NF,(D(ISYS,J),J=11,NFP)
           WRITE(IW,120)
           NF=IFIX(D(ISYS,20))
           NFP=NF+21
           WRITE(IW,160)NF,(D(ISYS,J),J=21,NFP)
           WRITE(IW,120)
           NF=IFIX(D(ISYS,30))
           NFP=NF+31
           WRITE(IW,165)NF,(D(ISYS,J),J=31,NFP)
           WRITE(IW,120)
           NF=IFIX(D(ISYS,40))
           NFP=NF+41
           WRITE(IW,170)NF,(D(ISYS,J),J=41,NFP)
           WRITE(IW,120)
           NF=IFIX(D(ISYS,50))
           NFP=NF+51
           WRITE(IW,175)NF,(D(ISYS,J),J=51,NFP)
           WRITE(IW,120)
           GO TO 30
C
C......RK - SIMULATION...............................
C
   25  WRITE(IW,180)(D(ISYS,J),J=10,14)
       WRITE(IW,120)
       WRITE(IW,185)(D(ISYS,J),J=20,24)
       WRITE(IW,120)
       WRITE(IW,190)(D(ISYS,J),J=30,34)
       WRITE(IW,120)
       WRITE(IW,195)(D(ISYS,J),J=40,44)
       WRITE(IW,120)
   30  WRITE(IW,200)(D(ISYS,J),J=2,6)
       DELAY = D(ISYS,9)-D(ISYS,7)
       WRITE(IW,205)(D(ISYS,J),J=7,9),DELAY
       WRITE(IW,210)(D(ISYS,J),J=80,83)
       WRITE(IW,120)
      IW=IR
       GO TO 70
C
C......SYSTEM SECTION...............................
C
  35   ISYS=2 + IG*3
       DO  40 J=1,9
          N(J)=IFIX(D(ISYS,J))
  40   CONTINUE
      IF(ILOG.EQ.ILP) IW=6
       NFIX=N(1)+N(2)+N(3)+1
       WRITE(IW,2150) RTYPE(ISYS)
       WRITE(IW,215)(N(J),J=1,8),NFIX,N(9)
       WRITE(IW,120)
       NF=N(1)+10
       WRITE(IW,220)(D(ISYS,J),J=10,NF)
       NF=N(2)+20
       WRITE(IW,225)(D(ISYS,J),J=20,NF)
       NF=N(3)+30
       WRITE(IW,230)(D(ISYS,J),J=30,NF)
       NF=N(4)+40
       WRITE(IW,235)(D(ISYS,J),J=40,NF)
       NF=N(5)+50
       WRITE(IW,240)(D(ISYS,J),J=50,NF)
       WRITE(IW,120)
       NF=IFIX(D(ISYS,60))
       NFP = NF+1
       IF(NFP .LT. 1 .OR. NFP .GT. 5) NFP = 1
       N1=IFIX(D(ISYS,64))
       N2=IFIX(D(ISYS,65))
       STD=2.75*SQRT( ABS( (D(ISYS-1,5)**2+0.00001)/30.0 ))
       WRITE(IW,245)NF,PRIDNT(NFP),(D(ISYS,J),J=61,63),N1,N2,D(ISY
     &            ,D(ISYS,67),STD
       WRITE(IW,120)
       WRITE(IW,250)(D(ISYS,J),J=70,75)
       WRITE(IW,120)
       WRITE(IW,255)(D(ISYS,J),J=80,85)
       WRITE(IW,120)
      IW=IR
       GO TO 70
C
C.......CONTROLER SECTION............................
C
  45   ISYS=3 + IG*3
       N1=IFIX(D(ISYS,1))
       IF(N1.LT.1 .OR. N1.GT.3) N1=1
       N2=IFIX(D(ISYS,5))
       NQ=IFIX(D(ISYS,10))
       NP=IFIX(D(ISYS,20))
       N3=IFIX(D(ISYS,30))
       NR=IFIX(D(ISYS,40))
       PCNT=(D(ISYS,3)-D(ISYS,2))*D(ISYS,4)/100.0
      IF(ILOG.EQ.ILP) IW=6
      WRITE(IW,2600) RTYPE(ISYS)
       WRITE(IW,260)N1,PRITYP(N1),(D(ISYS,J),J=2,4),PCNT
C
C........Q-FILTER..................
C
       WRITE(IW,265)N2,D(ISYS,6)
       IF(N2 .EQ. 0)    GO TO 55
          WRITE(IW,270)(D(ISYS,J),J=7,9)
          WRITE(IW,120)
C
C........ ESTIMATION OF EQUILANT Z-TRANSFORM............
C
          NQ = 1
          D(ISYS,15)=1.0
          D(ISYS,16)=0.0
          IF(D(ISYS,7) .GT. 0.0)  GO TO 50
          IF(D(ISYS,8) .EQ. 0.0)  GO TO 55
C
C.........INTEGRAL ACTION ONLY ...............
C
           NQ=2
           D(ISYS,11)=D(ISYS,8)
           D(ISYS,12)=0.0
           D(ISYS,16)=-1.0
           GO TO 55
   50    NQ=1
         D(ISYS,11)=D(ISYS,7)+D(ISYS,8)
         D(ISYS,12)=0.0
         D(ISYS,13)=D(ISYS,9)
         D(ISYS,16)=0.0
         IF(D(ISYS,8) .LE. 0.0)  GO TO 55
            NQ=2
            D(ISYS,12)=-D(ISYS,7)-2.*D(ISYS,9)
            D(ISYS,16)=-1.0
            IF(D(ISYS,9) .GT. 0.0) NQ=3
   55  WRITE(IW,275)NQ,(D(ISYS,J),J=11,14)
       WRITE(IW,280)   (D(ISYS,J),J=15,18)
       D(ISYS,10)=NQ
C
C..... P - FILTER ...............................
C
       WRITE(IW,120)
       NA = 1
       ITYP = IFIX(D(ISYS,20))
       TS   = D(ISYS-2,2)
       WRITE(IW,285)ITYP,TS
       IF(ITYP.NE. 1) GO TO 60
```

```
          ITYPS=IFIX(D(ISYS,21))
          GAIN =     D(ISYS,22)
          T(1) =     D(ISYS,23)
          T(2) =     D(ISYS,24)
          T(3) =     D(ISYS,25)
          WRITE(IW,290)ITYPS,GAIN,(T(J),J=1,3)
          CALL ZTRAN(ITYPS,TS,GAIN,T,A,B,NA,NB)
          D(ISYS,30)=FLOAT(NA)
          D(ISYS,31)=B(1)
          D(ISYS,32)=B(2)
          D(ISYS,33)=B(3)
          D(ISYS,34)=B(4)
          D(ISYS,35)=A(1)
          D(ISYS,36)=A(2)
          D(ISYS,37)=A(3)
          D(ISYS,38)=A(4)
   60  WRITE(IW,295)NA,(D(ISYS,J),J=31,34),(D(ISYS,J),J=35,38)
C
C..... R - FILTER..................................
C
       WRITE(IW,120)
       WRITE(IW,300)(D(ISYS,J),J=50,54)
       WRITE(IW,301)D(ISYS,60)
       WRITE(IW,302)(D(ISYS,J),J=61,63)
       WRITE(IW,303)(D(ISYS,J),J=64,66)
   65  ISYS=ISYS
       WRITE(IW,120)
      IW=IR
C......INPUT OUTPUT SECTION
C
   70  WRITE(IW,130)ICHAR,ICHARS,IG
       READ (IR,310)ICHAR2
C
C......CHANGE  , CHANGES , RESET , PRINT ,.........
C
       IF(ICHAR2 .EQ. KC    ) GO TO 75
       IF(ICHAR2 .EQ. KS    ) GO TO 80
       IF(ICHAR2 .EQ. KR    ) GO TO 15
       GO TO 70
C
C....... SINGLE INPUT
C
   75  WRITE(IW,140)
       READ(IR,*)N1,AIN(1)
       IF(N1.LT.1 .OR. N1 .GT. 100) WRITE(IW,135)
       IF(N1.LT.1 .OR. N1 .GT. 100) GO TO 70
       D(ISYS,N1)=AIN(1)
       GO TO 70
C
C.......MULTI-INPUT 10 NUMBER.....................
C
```

```
   80  WRITE(IW,145)
       READ(IR,*)N1,(AIN(J),J=1,10)
       IF(N1.GT.90) WRITE(IW,135)
       IF(N1 .GT. 90) GO TO 70
       DO  85 J=1,10
           JM1=J+N1-1
           D(ISYS,JM1)=AIN(J)
   85  CONTINUE
       GO TO 70
C
C
   90 CONTINUE
C     CALL CLOSE(IDCB,IERR)
C     CALL OPEN(IDCB,IERR,IFILE,0,77,146,170)
      CALL RWNDF(IDCB,IERR)
      IF(IERR .GE. 0) GO TO 91
      STOP 4
  91   DO 95 J=1,6
C
C
      DO 820  I = 1,40
      BUF(I) = D(J,I)
 820  CONTINUE
           CALL WRITF(IDCB,IERR,BUF,80)
      DO 822  I = 41,85
      IDUM = I - 40
      BUF(IDUM) = D(J,I)
 822  CONTINUE
             CALL WRITF(IDCB,IERR,BUF,90)
      IF(IERR .GE. 0) GO TO 97
      CALL FMGER(IERR)
      STOP 4
97     CONTINUE
         WRITE(IW,305)J
95     CONTINUE
       CALL CLOSE(IDCB,IERR)
      STOP
  100 FORMAT(5G12.5)
  105 FORMAT(I7,10G12.5)
  110 FORMAT(5G12.5)
  115 FORMAT(5(G12.5,1X))
  120 FORMAT(1X,60(1H-))
  125 FORMAT(1X,'MODEL  ,  SYSTEM , CONTROL-ACTION  ,  RUN ',/,
     1     1X,'-          -       -                  -')
  130 FORMAT(1X,'CHANGE , CHANGES , RESET ,    <',2A1,I1,'> ',/,
     &     1X,'-                -    -')
  135 FORMAT(1X,'WRONG NUMBER OF INDEX TRY AGIAN')
  140 FORMAT(1X,'INPUT INDEX , VALUE')
  145 FORMAT(2X,'INPUT INDEX , VALUES ....<><>')
  150 FORMAT('<01> TYPE OF SIMULATION =',I2)
 1500 FORMAT('1',/////,' * * * ',A4,'MODEL * * *',///)
```

```
  155 FORMAT(1X,'<10> N( B1 )=',I2,/,
     1      (1X,'<11>    B1  =',5G12.5) )
  160 FORMAT(1X,'<20> N( B2 )=',I2,/,
     1      (1X,'<21>    B2  =',5G12.5) )
  165 FORMAT(1X,'<30> N( D1 )=',I2,/,
     1      (1X,'<31>    D1  =',5G12.5) )
  170 FORMAT(1X,'<40> N( C1 )=',I2,/,
     1      (1X,'<41>    C1  =',5G12.5) )
  175 FORMAT(1X,'<50> N( A  )=',I2,/,
     1      (1X,'<51>    A   =',5G12.5) )
  180 FORMAT(1X,'<10> T-RK =',F2.0,'  FOR  G(11)',/,
     1       1X,'<11> GAIN =',G12.5,'<12-14> T=',3G12.5)
  185 FORMAT(1X,'<20> T-RK =',F2.0,'  FOR  G(12)',/,
     1       1X,'<21> GAIN =',G12.5,'<22-24> T=',3G12.5)
  190 FORMAT(1X,'<30> T-RK =',F2.0,'  FOR  G( D)',/,
     1       1X,'<31> GAIN =',G12.5,'<32-34> T=',3G12.5)
  195 FORMAT(1X,'<40> T-RK =',F2.0,'  FOR  G( C)',/,
     1       1X,'<41> GAIN =',G12.5,'<42-44> T=',3G12.5)
  200 FORMAT(1X,'<02> T-SA =',G12.5,
     1       1X,'<03> RK-DT=',G12.5,'<04> RK-NO=',F3.0,/,
     2       1X,'<05> ST-DI=',G12.5,'  <06> N-LIM=',G12.5)
  205 FORMAT(1X,'<07> K11=',F3.0,' <08> K12=',F3.0,
     &       1X,'<09> KD =',F3.0,1X,F3.0)
  210 FORMAT(' <80> ADC   Y=',G12.5,' *  SADC + ',G12.5,/,
     &       ' <82> DAC U.S=',G12.5,' *  UN   + ',G12.5)
 2150  FORMAT('1',/////,' * * * ',A4,'SYSTEM * * *',///)
  215 FORMAT('<01> NG1=',I2,' <02> NF =',I2,' <03> ND =',I2,/,
     1       1X,'<04> NH =',I2,' <05> NG2=',I2,/,
     2       1X,'<06> K1 =',I2,' <07> K2 =',I2,' <08> KD =',I2,/,
     3       1X,'  FIX-N =',I2,' <09>NDEL=',I2 )
  220 FORMAT(1X,'<10> G1 =',5G12.5)
  225 FORMAT(1X,'<20> F  =',5G12.5)
  230 FORMAT(1X,'<30> D  =',5G12.5)
  235 FORMAT(1X,'<40> H  =',5G12.5)
  240 FORMAT(1X,'<50> G2 =',5G12.5)
  245 FORMAT(1X,'<60> TYPE OF IDENT=',I2,'    ',A4,/,
     1       1X,'<61> ROW-1=',G12.5,' <62> ROW-2=',G12.5,/,
     2       1X,'<63> P-INT=',G12.5,' <64> I-FIX=',2I3,/,
     3       1X,'<66> G*COP=',G12.5,' <67> L-PHI=',2G12.5)
  250 FORMAT(1X,'<70> TYPE OF SET-POINT=',F2.0,/,
     1       1X,'<71> HIEGHT =',G12.5,' <72> LEINGHT=',G12.5,/,
     2       1X,'<73> START  =',G12.5,' <74> FINAL  =',G12.5,/,
     3       1X,'<75> BASE   =',G12.5)
  255 FORMAT(1X,'<80> TYPE OF DISTURBANCE=',F2.0,/,
     1       1X,'<81> HIEGHT =',G12.5,' <82> LEINGHT=',G12.5,/,
     2       1X,'<83> START  =',G12.5,' <84> FINAL  =',G12.5,/,
     3       1X,'<85> BASE   =',G12.5)
  2600 FORMAT('1',/////,' * * * ',A4,'CONTROL * * *',///)
  260 FORMAT('<01> TYPE OF CONTROLLER=',I2,4X,A4,/,
     1       1X,'<02> LOWER-U=',G12.5,' <03> UPPER-U=',G12.5,/,
     2       1X,'<04> PERCENT=',G12.5,'  USTEP      =',G12.5)
  265 FORMAT(1X,'<05> TYPE OF PID=',I2,10X,' 0 --> Z-TRAN',/,
     1       1X,  28X,                      ' 1 --> S-TRAN',/,
     2       1X,'<06> PID-ACTION=',G12.5)
  270 FORMAT(1X,'<07> KP   =',G12.5,/,
     1       1X,'<08> KI   =',G12.5,/,
     2       1X,'<09> KD   =',G12.5)
  275 FORMAT(1X,'Q-FILTER....',/,1X,'<10> NQ   =',I2,/,
     1       1X,'<11> QD(Z)=',5G12.5,(/,10X,5G12.5))
  280 FORMAT(1X,'<15> QN(Z)=',5G12.5,(/,10X,5G12.5))
  285 FORMAT(1X,'P-FILTER....',/,
     &       1X,'<20> TYPE =',I2,10X,' 0 ---> Z-TRAN',/,
     &       1X,'     T-S  =',G12.5 ,' 1 ---> S-TRAN')
  290 FORMAT(1X,'<21> T-RK=',I2,/,
     &       1X,'<22> GAIN =',G12.5,' <23-25> T=',3G12.5)
  295 FORMAT(1X,'<30> NP   =',I2,/,
     &       1X,'<31> PN   =',4G12.5,/,
     &       1X,'<35> PD   =',4G12.5)
  300 FORMAT(1X,'R FILTER....',/,1X,'<50> T-RK=',F2.0,/,
     1 1X,'<51>  GAIN=',G12.5,' <52-53> T=',2G12.5,'<54> K=',F2.0)
  301 FORMAT(1X,'<60> U-STEADY-STATE=',G12.5)
  302 FORMAT(1X,'    PID SETTINGS (AKPS,AKIS,AKDS)',/,
     &       1X,'    POSITIONAL OR INCREMENTAL CONTROLLER',/,
     1 1X,'<61-63> ',3G12.5)
  303 FORMAT(1X,'    Q-FILTER SETTINGS (AKP,AKI,AKD)',/,
     &       1X,'<64-66> ',3G12.5)
  305 FORMAT(' SECTOR ',I2,' HAS BEEN WRITTEN ')
  310 FORMAT(2A1,A2)
  315 FORMAT(I1)
      END
```

```
&ERSUM T=00004 IS ON CR00146 USING 00011 BLKS R=0087
FTN4
      PROGRAM ERSUM( ,101)
C
      DIMENSION IDCB(144),BUF(56),ISTR(20),
     *          I1(20),I2(20),IR(20),
     *          IFILE(3),LU(5),
     *          FEED1(20),FEED2(20),SIAE(20)
C
      CALL RMPAR(LU)
      LUN=LU(1)
C
C
      WRITE(LUN,1000)
      READ(LUN,1002) (IFILE(I),I=1,3),ICR
C
      WRITE(LUN,1006)
      READ(LUN,*) MAXREG
C
      WRITE(LUN,1010)
      READ(LUN,*) ILU

C
C
          DO 50 IREG = 1,MAXREG
          WRITE(LUN,1012) IREG
          READ(LUN,*) I1(IREG),I2(IREG),IR(IREG)
   50 CONTINUE
C
C
C
C
      CALL OPEN(IDCB,IERR,IFILE,0,77,ICR,144)
      IF(IERR.GE.0) GOTO 70
      CALL FMGER(IERR)
      STOP
C
C-  READ HEADER RECORD.
C
   70 CONTINUE
      CALL READF(IDCB,IERR,BUF,40,ILEN)
      IF(IERR.LT.0) CALL FMGER(IERR)
      WRITE(ILU,1020) (BUF(I),I=1,20)
      DO 900   IREG = 1,MAXREG
C
      IBEG = I1(IREG)
      IEND = 0
      IDUM = IREG - 1
      IF(IREG .NE. 1) IEND = ISTR(IDUM) + IR(IDUM) - 1
      IRW  = IBEG - IEND -1
      CALL POSNT(IDCB,IERR,IRW,0)
                CALL HSIAE(IDCB,BUF,ISTR(IREG),BEG,END,
     *                           SIAE(IREG),FEED1(IREG),FEED2(IREG),
     *                           I1(IREG),I2(IREG),IR(IREG))
      WRITE(ILU,1022) IREG,BEG,END
1022  FORMAT(' REGION ',I4,' BEGINS AT ',F7.2,' ENDS AT ',F7.2)
C
C
 900  CONTINUE
C
C-  PRINT OUT SIAE RESULTS.
C
      CALL RWNDF(IDCB,IERR)
      CALL READF(IDCB,IERR,BUF,40,ILEN)
      WRITE(ILU,951) (BUF(I),I=1,20)
C
           DO 950  IREG = 1,MAXREG
             WRITE(ILU,953) IREG,I1(IREG),I2(IREG),
     *                            ISTR(IREG),FEED1(IREG),FEED2(IREG),
     *                            IR(IREG),SIAE(IREG)
 950       CONTINUE
C
      CALL CLOSE(IDCB,IERR)
      STOP
C
C-------------------------------------------------------------------
C-
C-  FORMAT STATEMENTS.
C-
C
 951  FORMAT(//,' * * FOR FILE ON * * ',/,20A4,/)
 953  FORMAT(/,' FOR REGION ',I2,5X,' FROM: ',I4,' TO: ',I4,
     *       /,' FEED CHANGE AT',I4,5X,' FROM: ',F6.3,' TO: ',F6.3
     *       /,' SIAE AFTER ',I2,' ITERATION IS =',F10.4)
1000  FORMAT(/,' ENTER FILENAME(3A2) AND CARTRIDGE(I3): ','_')
1002  FORMAT(3A2,I3)
1006  FORMAT(/,' ENTER NO. OF REGION (MAX=20): ','_')
1010  FORMAT(/,' ENTER OUTPUT DEVICE: ','_')
1012  FORMAT(/,' FOR REGION: ',I2,
     *       /,' ENTER START,FINAL AND NO. OF ITERATIONS: ','_')
1020  FORMAT(/,' PLOTTING FOR ',/,20A4)
      END
```

```
&HPL01 T=00004 IS ON CR00136 USING 00028 BLKS R=0000

C
C*  THIS PROGRAM PLOTS DATA STORED IN DATA FILE.
C
FTN4
      PROGRAM HPLOT( ,101)
C
      DIMENSION IDCB(144),BUF(56),X(702),Y(702),
     *          I1(15),I2(15),IR(15),
     *          SPAN(6),ZERO(6),IFLO(6),Y00(6),
     *          IPOS(11),SSTART(11,15),RRANGE(11,15),
     *          NPAR(5),IFILE(3),LU(5),
     *          DSTART(6),DRANGE(6)
C
      DATA IPOS/9,10,12,11,13,14,17,0,0,0,0/,
     *     CONA/1.0/,CONB/0./,
     *     IFLO/0,1,1,0,1,1/,
     *     SPAN/.12857,2.2975,2.5517,1.,2.50,1.3140/,
     *     ZERO/89.167,0.,0.,0.,0.,0./,
     *     SSTART/110*0./,RRANGE/110*0./,
     *     Y00/0.,4.,5.5,0.,4.,5.5/,
     *     DSTART/93.5,0.00,12.0,1.00,0.00,0.00/,
     *     DRANGE/1.00,0.00,12.00,3.00,0.00,0.00/
      CALL RMPAR(LU)
      LUN=LU(1)
C
C*  OBTAIN INFORMATION ON WHERE DATA IS STORED
C
      WRITE(LUN,1000)
      READ(LUN,1002) (IFILE(I),I=1,3),ICR
C
      WRITE(LUN,1004)
      READ(LUN,*) (NPAR(I),I=1,5)
C
      WRITE(LUN,1006)
      READ(LUN,*) MAXREG
C
      WRITE(LUN,1008)
      READ(LUN,*) IYOPT
C
      WRITE(LUN,1010)
      READ(LUN,*) ILU
C
      WRITE(LUN,1011)
      READ(LUN,*) ST

C
C*  READ IN INFORMATION FOR EACH REGION.
C
```

```
           DO 50 IREG = 1,MAXREG
           WRITE(LUN,1012) IREG
           READ(LUN,*) I1(IREG),I2(IREG),IR(IREG)
C
           WRITE(LUN,1014)
           READ(LUN,*)IDUM
           IF(IDUM.NE.1) GO TO 20
C
C*  OBTAIN RANGE AND START PONT OF EACH REGION FOR PROCESS MEASURE
C
           WRITE(LUN,1016) MAXREG
           READ(LUN,*) (SSTART(I,IREG),I=1,6)
           WRITE(LUN,1017) MAXREG
           READ(LUN,*) (RRANGE(I,IREG),I=1,6)
C
  20       IF(IDUM.NE.2) GO TO 22
C
C- TAKE DEFAULT SCALING.
C
           DO 24  I= 1,6
           SSTART(I,IREG) = DSTART(I)
           RRANGE(I,IREG) = DRANGE(I)
  24       CONTINUE
C
  22       WRITE(LUN,1018)
           READ(LUN,*) IDUM
           IF(IDUM.NE.1) GO TO 30
C
C*  WANT START AND RANGE OF PARAMETERS.
C
           WRITE(LUN,1016) MAXREG
           READ(LUN,*) (SSTART(I,IREG),I=7,11)
           WRITE(LUN,1017) MAXREG
           READ(LUN,*) (RRANGE(I,IREG),I=7,11)
C
  30       CONTINUE
C
  50  CONTINUE
C
C*  OBTAIN THE STARTING POSITION OF EACH TYPE OF PARAMETER
C
      DO 60  I = 8,11
           IDUM = I - 1
           IDU1 = I - 7
           IPOS(I) = IPOS(IDUM) + NPAR(IDU1)
  60  CONTINUE
C
C
      CALL OPEN(IDCB,IERR,IFILE,0,77,ICR,144)
      IF(IERR.GE.0) GOTO 70
      CALL FMGER(LUN,IERR)
      STOP
C
C-  READ HEADER RECORD.
C
  70  CONTINUE
      CALL READF(IDCB,IERR,BUF,40,ILEN)
      IF(IERR.LT.0) CALL FMGER(LUN,IERR)
      WRITE(LUN,1020) (BUF(I),I=1,20)
      DO 900   IREG = 1,MAXREG
C
      WRITE(LUN,2040)
        IBEG = I1(IREG)
        IEND = 0
        IF(IREG .NE. 1)IEND = I2(IREG-1)
        IRW  = IBEG - IEND - 2
        CALL POSNT(IDCB,IERR,IRW,0)
        CALL LOCF(IDCB,IERR,IREC,IRB,IOFF)
C
C*  FILL IN TIME INFORMATION (X-AXIS).
C
           J = 0
                DO 100 I = I1(IREG),I2(IREG),IR(IREG)
                      J= J + 1
                      X(J) = FLOAT(I-I1(IREG))*ST
 100            CONTINUE
C
C*  COMPUTE NO. OF POINTS TO BE PLOTTED
C
           NPT = I2(IREG) - I1(IREG) + 1
C
C*  INITIALIZE PLOTTING.
C
           CALL PLOTS(0.0,ILU)
           IF(ILU.EQ.4) CALL FACTOR(.6)
           CALL PLOT(1.87,1.61,-3)
           CALL HCALE(X,5.0,NPT,1)
C
C*  DETERMINE WHICH OPTION TO PLOT.
C
           IBEG = 1
           IEND = 3
           IF(IYOPT.EQ.1 .OR. IYOPT.EQ.3) GOTO 150
C
           IBEG = 4
           IEND = 6
           IF(IYOPT.EQ.2) GOTO 150
C
           IBEG = 1
 150       CONTINUE
C
C
```

```
C-  START PLOTTING THE FLOW MEASUREMENT.
C
           DO 200 I = IBEG,IEND
                ITYP = I
C
C-  IF ONLY PLOTTING BOTTOM, PLOT FEED INSTEAD OF REFLUX.
C
                IF(IYOPT.EQ.2 .AND. ITYP.EQ.6) ITYP = 3
                IF(IYOPT.EQ.3 .AND. ITYP.EQ.2) ITYP = 4
                START = SSTART(ITYP,IREG)
                RANGE = RRANGE(ITYP,IREG)
C
C*  CALL SUBROUTINE TO PLOT OUT MEASUREMENT FOR EACH REGION.
C
                CALL HPLT(IDCB,BUF,X,Y,IREC,IRB,IOFF,
     *                    I1(IREG),I2(IREG),IR(IREG),BEG,END,
     *                    IPOS(ITYP),SPAN(ITYP),ZERO(ITYP),YOO(I),
     *                    IFLO(ITYP),START,RANGE,ITYP)
       IF(ITYP.EQ.3.AND.IEND.EQ.6.AND.IYOPT.EQ.4) CALL PLOT(0.,-9.
                WRITE(LUN,2000) ITYP,IREG
                WRITE(LUN,2020) BEG,END
2020            FORMAT(' PLOTTING FROM ',F7.2,' TO ',F7.2)
 200       CONTINUE
C
C*  PLOT OUT PARAMETERS FOR EACH REGION.
C
           IF(ILU .EQ. 4) GO TO 800
           CALL PLOT(0.,-9.5,-3)
           CALL PLOT(1.397,.2733,-3)
C
C
           DO 300  I = 1,5
                ITYP = 6 + I
C
                START = SSTART(ITYP,IREG)
                RANGE = RRANGE(ITYP,IREG)
C
C*  CALL SUBROUTINE TO PLOT OUT PARAMETERS FOR EACH REGION.
C
                CALL HPLT(IDCB,BUF,X,Y,IREC,IRB,IOFF,
     *                    I1(IREG),I2(IREG),IR(IREG),BEG,END,
     *                    IPOS(ITYP),CONA,CONB,YOO(1),NPAR(I),0,
     *                    START,RANGE,ITYP)
                WRITE(LUN,2000)ITYP,IREG
                WRITE(LUN,2020)BEG,END
C
 300       CONTINUE
           CALL PLOT(-1.397,-.2733,-3)
 800       CALL PLOT(0.,0.,999)
C
C
```

```
  900  CONTINUE
C
       CALL CLOSE(IDCB,IERR)
       STOP
C
C-----------------------------------------------------------------
C-
C-  FORMAT STATEMENTS.
C-
C
  1000 FORMAT(/,' ENTER FILENAME(3A2) AND CARTRIDGE(I3): ','_')
  1002 FORMAT(3A2,I3)
  1004 FORMAT(/,' ENTER NO. OF G1,F,D,H,G2 PARAMENTERS: _')
  1006 FORMAT(/,' ENTER NO. OF REGION (MAX=10): ','_')
  1008 FORMAT(/,' ENTER 1 = TOP, 2 = BOTTOM, 3 = FD,TC,BC, 4 = ALL:  '
  1010 FORMAT(/,' ENTER PLOT DEVICE (4=HP2648  6=LP): ','_')
  1011 FORMAT(/,' ENTER SAMPLE TIME IN MINUTES:_')
  1012 FORMAT(/,' FOR REGION: ',I2,
      *,/,' ENTER START, FINAL AND REPEAT FACTOR: ','_')
  1014 FORMAT(/,' ENTER:  0-AUTOSCALE 1-MANUAL ENTRY 2-DEFAULT: ','
  1016 FORMAT(' ENTER ',I2,' START VALUE FOR REGIONS, 0 = AUTO SCAL
  1017 FORMAT(' ENTER ',I2,' RANGE FOR DIFFERENT REGION (UNITS/TICK
  1018 FORMAT(/,' WANT TO ENTER SCALE FACTOR FOR PARAM.',
      *          '(1 - YES): _')
  1020 FORMAT(' * * PLOTTING FOR * *',/,20A4)
  2000 FORMAT(/,' * * COMPLETED TYPE ',I2,'  FOR REGION ',I2,' * *'
  2040 FORMAT(/)
       END
```

```
&HPLT2 T=00004 IS ON CR00136 USING 00017 BLKS R=0000

C
C*  THIS SUBROUTINE DOES THE ACTUAL PLOTTING FOR EACH REGION.
C
FTN4
      SUBROUTINE HPLT(IDCB,BUF,X,Y,IREC,IRB,IOFF,
     *                I1,I2,IR,BEG,END,
     *                IPOS,SPAN,ZERO,Y00,NPAR,IFLO,
     *                START,RANGE,ITYP)
C
      DIMENSION IDCB(1),BUF(1),X(1),Y(1)
      DATA ILEN/112/,IFLG/1/
      IF(NPAR .EQ. 0) GO TO 500
C
C
      NPT = I2 - I1 + 1
      K = 0
C
C
      DO 100  II = 1,NPAR
           J = 0
           CALL APOSN(IDCB,IER,IRCD,IRB,IOFF)
           CALL READF(IDCB,IERR,BUF,20,ILEN)
           IVAL = IPOS + K
           K    = K    + 1
C
C
           DO 110  I = 1,NPT
                CALL READF(IDCB,IERR,BUF,112,ILEN,LEN)
                IF(ILEN .EQ. -1) GO TO 900
                IF(I .EQ. 1) BEG = BUF(3)
                IF(I .EQ. NPT) END = BUF(3)
C
                     J = J + 1
                     Y(J) = BUF(IVAL)
                     IF(IFLO.EQ.1) Y(J) = SQRT(Y(J))
                     Y(J) = SPAN * Y(J)  +  ZERO
 110       CONTINUE
C
C
      IF(K .NE. 4) GO TO 120
           CALL PLOT(0.,0.,10)
           CALL PLOT(0.,-7.,-3)
C
 120  CONTINUE
      X0=0
      IF(Y00 .EQ. 0.) GO TO 200
      Y0 = Y00
      GOTO 210
```

```
C
  200 YO = 3.5
      IF(II.EQ.1 .OR. II.EQ.4) YO = 0.
C
  210 CALL PLOT(XO,YO,-3)
C
C-  START PLOTTING.
C
      N=NPT
      CALL SYMBOL(1.88,-.55,.15,10HTIME (MIN),0.0,10)
      CALL AXIS(0.,0.,20H                    ,
     *          -20,5.0,0.0,X(N+1),X(N+2))
           Y(N+1) = START
           Y(N+2) = RANGE
           IF(START .EQ. 0.) CALL HCALE(Y,3.0,NPT,1)
      GOTO(1,2,3,4,5,6,7,8,9,10,11) ITYP
C
    1 CALL SYMBOL(-.4,.975,.15,10HXD - [WT%],90.0,10)
      CALL AXIS(0.,0.,0,0,3.0,90.0,Y(N+1),Y(N+2))
      GOTO 250
C
    2 CALL SYMBOL(-.4,.975,.15,10HRE - [G/S],90.0,10)
      CALL AXIS(0.,0.,0,0,3.0,90.,Y(N+1),Y(N+2))
      GOTO 250
C
    3 CALL SYMBOL(-.4,.975,.15,10HFE - [G/S],90.0,10)
      CALL AXIS(0.,0.,0,0,2.0,90.,Y(N+1),Y(N+2))
      GOTO 250
C
    4 CALL SYMBOL(-.4,.975,.15,10HXB - [WT%],90.0,10)
      CALL AXIS(0.,0.,0,0,3.0,90.,Y(N+1),Y(N+2))
      GOTO 250
C
    5 CALL SYMBOL(-.4,.975,.15,10HST - [G/S],90.0,10)
      CALL AXIS(0.,0.,0,0,3.0,90.,Y(N+1),Y(N+2))
      GOTO 250
C
    6 CALL SYMBOL(-.4,.975,.15,10HDI - [G/S],90.0,10)
      CALL AXIS(0.,0.,0,0,3.0,90.0,Y(N+1),Y(N+2))
      GOTO 250
C
    7 CALL SYMBOL(-.4,.975,.15,10HPARAM - G1,90.0,10)
      CALL AXIS(0.,0.,18H                  ,18,3.0,90.,
     *          Y(N+1),Y(N+2))
      GOTO 250
C
    8 CALL SYMBOL(-.4,.975,.15,10HPARAM - F ,90.0,10)
      CALL AXIS(0.,0.,18H                  ,18,3.0,90.,
     *          Y(N+1),Y(N+2))
      GOTO 250
C
```

```
    9 CALL SYMBOL(-.4,.975,.15,10HPARAM - D ,90.0,10)
      CALL AXIS(0.,0.,18H                  ,18,3.0,90.,
     *          Y(N+1),Y(N+2))
      GOTO 250
C
   10 CALL SYMBOL(-.4,.975,.15,10HPARAM - H ,90.0,10)
      CALL AXIS(0.,0.,18H                  ,18,3.0,90.,
     *          Y(N+1),Y(N+2))
      GOTO 250
C
   11 CALL SYMBOL(-.4,.975,.15,10HPARAM - G2,90.0,10)
      CALL AXIS(0.,0.,18H                  ,18,3.0,90.,
     *          Y(N+1),Y(N+2))
C
  250 CONTINUE
      CALL LINE(X,Y,NPT,1,0,1)
  100 CONTINUE
C
C
      IF(ITYP.EQ.3 .OR. ITYP.GE.6) CALL PLOT(0.,0.,10)
C
C-  CHECK IF WE HAVE TO RESET THE ORIGIN.
C
      IF(NPAR.EQ.1 .OR. NPAR.EQ.4) YO = 0
      IF(NPAR.EQ.2 .OR. NPAR.EQ.5) YO = -3.50
      IF(NPAR.EQ.3 .OR. NPAR.EQ.6) YO = -7.
      CALL PLOT(0.,YO,-3)
C
  500 CONTINUE
      RETURN
C
C
  900 WRITE(LUN,999)
  999 FORMAT(' REACHED END OF FILE ')
      CALL CLOSE(IDCB,IERR)
      STOP
      END
```

&GCLN2 T=00003 IS ON CR00139 USING 00012 BLKS R=0000

```
FTN4
      PROGRAM GCLNK (3,70), GC DATA TRANSFER, 790301, VFB
C
C
C         THIS PROGRAM IS USED TO RECEIVE GC DATA FROM A REMOTE
C         CPU. IT USES CLASS I/O TO RECEIVE THE DATA.
C         THE PROGRAM IS ALWAYS READY TO RECEIVE THE DATA.
C         THE PROGRAM STORES DATA IN REAL TIME COMMON AREA.
C         START OF THE AREA MUST BE SET UP IN REAL TIME
C         COMMON POINTER AREA. CURRENTLY POINTER 4, WORD 8
C         OF RT COMMON IS USED TO POINT TO THE GC DATA AREA.
C         THE LENGTH OF THE AREA IS 80 WORDS.
C
C
C
C
      COMMON / / ICOM(1)
      DIMENSION IBUF(50,10), ICLAS(10)
C
C         INITIALIZE I/O, CHECK STATUS, LOCK RECEIVING UNIT,
C         START CLASS I/O AND
C         SET UP COMMON ADDRESSING
C
      DATA LUGC/33/, NBUF/10/, NEXT/0/
      DATA IRLEN/50/,LEN/50/
      DATA ICLAS/10*100000B/
      IAS=ICOM(8)
      IAD=IAS+6
      ICOM(IAS)=0
      LU=LOGLU(ISESN)
      CALL EXEC (13,LUGC,IST1,IST2,IST3)
      IF (IST3.LT.0) GO TO 800
      CALL LURQ(1,LUGC,1)
C     CALL EXEC (22,1)
         DO 100 I=1,NBUF
         II=I
         CALL EXEC(17,LUGC,IBUF(1,I) ,IRLEN,IP1,IP2,ICLAS(I))
         CALL ABREG (IA,IB)
D        WRITE (LU,1030) IA,IB
D1030    FORMAT (" ALOCATE 1: IA,IB=",208)
         IF (IA.LT.0) GO TO 110
         ICLAS(I)=IAND(ICLAS(I),077777B)
  100    CONTINUE
C
  110 NBUF=II-1
      WRITE(LU,1035) NBUF
 1035 FORMAT(1X,"NUMBER OF BUFFERS=",I3)
C     ICLAS=IOR (ICLAS,20000B)
```

```
C     ICLAS=IAND(ICLAS,077777B)
C
C
C      START OF INPUT LOOP
C
C
  500 CONTINUE
C
      DO 200 IBUFN=1,NBUF
      CALL EXEC(21,ICLAS(IBUFN),IBUF(1,IBUFN),LEN,IP1,IP2,IP3)
      CALL ABREG(IA,IBUFL)
D     WRITE (LU,1050) IA,IBUFL
D1050 FORMAT(" GET 1: IA, IBUFL=",208)
      ICLAS(IBUFN)=0
      IF (IBUFL.EQ.0) GO TO 130
      IF (IBUFL.LT.0.OR.IBUFL.GT.40) GO TO 150
D     WRITE (LU,1060) (IBUF(III,IBUFN),III=1,IBUFL)
D1060 FORMAT(1X,20A2)
      IF (IAD+IBUFL.GT.IAS+ICOM(9)-1) IAD=IAS+6
D     WRITE(LU,1070) LUGC,IRLEN,LEN,IBUFN,IAD
 1070 FORMAT("LUGC,IRLEN,LEN,IBUFN,IAD="/
     25I10)
C
         DO 120 J=1,IBUFL
         ICOM(IAD+J)=IBUF(J,IBUFN)
  120    CONTINUE
C
  130 IF (ICOM(IAS).EQ.0)  GO TO 140
      NEXT=NEXT+1
      IF (NEXT.GE.NBUF) GO TO 999
      GO TO 200
C
  140 IAD=IAD+IBUFL
  150 CALL EXEC (17,LUGC,IBUF(1,IBUFN),IRLEN,IP1,IP2,ICLAS(IBUFN))
      CALL ABREG (IA,IB)
D     WRITE (LU,1030) IA,IB
  200 CONTINUE
      GO TO 500
C
C     END OF INPUT LOOP
C
C
  800 CALL ABORT (0,1,25H***GC LINK UNIT DOWN  ***)
  999 CALL LURQ(0,LUGC,1)
      STOP
      END
```

```
FTN4
      PROGRAM GCSCH(3,80), PROGRAM TO INITIATE GC ON COLUMN HYL790
      COMMON ICOM(1)
      DIMENSION INAME1(3),INAME2(3)
      DATA INAME1/2HGC,2HSW,2HT /,INAME2/2HSE,2HGS,2HT /
      ISTR=ICOM(8)
      ILEN=ICOM(9)-7
      LUN=ICOM(ISTR+3)
      IMAX=ICOM(ISTR+4)
      IDFLT = ICOM(ISTR + 5)
C
      CALL BOTCM(ISTR,ILEN,LUN,IMAX)
      CALL DOL(1,1,4,4,IERR)
      IF(IERR.NE.1) GO TO 500
C
C*  SCHEDULE GCSWT TO RESET GC START BUTTON.
C
      CALL EXEC(10+100000B,INAME1)
      GO TO 950
      STOP
C
C*  IF ERROR DETECTED, TURN PROGAM OFF AND SET COMPOSITION TO DEFA
C
  500 WRITE(LUN,600)IERR
  600 FORMAT("PROGRAM GCSCH FAILED TO CLOSE DITIGAL SWITCH, IERR -
      GO TO 999
C
  950 WRITE(LUN,952)
  952 FORMAT("SCHEDULE OF GCSWT UNSUCCESSFUL")
C
  999 ICOM(ISTR+1) = IDFLT
      CALL EXEC(10,INAME2)
      STOP
      END
C
C
C
      SUBROUTINE BOTCM(ISTR,ILEN,LUN,IMAX)
      COMMON ICOM(1)
      DIMENSION CON(6), IVAL(4), ITIME(5)
      DATA CON/100.,1.,.1,.001,10.,.01/,IBLANK/2H  /
      ICHR=2H &
C
C*  SEARCH FOR CHARACTER STRING "&".  THE COMPOSITION OF WATER WIL
C*  PRECEDE THIS STRING.
C
      IADD=ISTR+6
      DO 10 I=1,ILEN
      IPRE=I
      IF(ICOM(IADD+IPRE).EQ.ICHR) GO TO 12
```

```
 10   CONTINUE
      GO TO 500
C
C*  STORE ASCII REPRESENTATION OF COMPOSITION INTO ARRAY IVAL.
C
 12   DO 20 I=1,4
      IPOS=IPRE-I
      IF(IPOS.LT.0) IPOS=ILEN+IPOS+1
      IVAL(5-I)=ICOM(IADD+IPOS)
 20   CONTINUE
C
C*  CONVERT THE VALUE IN ASCII INTO A DECIMAL NUMBER.
C
      VALU=0.
      DO 30 I=1,4
      IDUM=IAND(ISHFT(IVAL(I),-8),377B)
      IF(IDUM.EQ.32) CON(I)=0.
      VALU=VALU+CON(I)*FLOAT(IDUM-48)
      IF((I.EQ.2).OR.(I.EQ.4)) GO TO 30
      IDUM=(I-1)/2+5
      IDU1=IAND(IVAL(I),377B)
      IF(IDU1.EQ.32) CON(IDUM)=0.
      VALU=VALU+CON(IDUM)*FLOAT(IDU1-48)
  30  CONTINUE
C
C
C*  CONVERT THE COMPOSITION TO AN INTEGER BETWEEN 0-32767 FOR METH
C*  NOTE: 1%=1000.
C
      VALU=100.-VALU
      IMET=IFIX(VALU*1000.)
      IF (LUN.NE.34) WRITE(LUN,103) VALU
 103  FORMAT(10X,"XB = ",F6.3)
C
C*  CHECK IF THE VALUE HAS CHANGED.
C
      IF(IMET.EQ.ICOM(ISTR+1)) GO TO 200
      IF(IMET .LT. 0) GO TO 220
C
C-  CHECK THAT GC READING HAS NOT CHANGE BY MAX  MAX IS STORED IN
C-  WORD OF GC AREA.
C
      IDIFF = IABS(ICOM(ISTR + 1) - IMET)
      IF(IDIFF. GT. ICOM(ISTR + 6) ) GOTO 300
C
      ICOM(ISTR + 2) = 0
      ICOM(ISTR+1)=IMET
C
C- BLANK OUT GC AREA IN RT COMMON.
C
      DO 25 I=1,ILEN
      II = I
      ICOM(IADD + II)  =  IBLANK
   25 CONTINUE
C
C
      RETURN
C
C*  IF GC READING REMAINS THE SAME FOR IMAX TIME, GC COMPUTER IS P
C*  DOWN, PUT OUTPUT SEGMENT OF STEAM FLOW ON MANUAL AND GIVE MESS
C
  200 ICOM(ISTR+2)=ICOM(ISTR+2)+1
      IF(ICOM(ISTR+2).LT.IMAX) RETURN
      WRITE(LUN,205)ICOM(ISTR+2)
      ICOM(ISTR+1) = ICOM(ISTR+5)
      RETURN
C
C
  220 WRITE(LUN,222)
      GOTO 600
C
C
  300 WRITE(LUN,310)
      GOTO 600
C
C*  IF I EQUAL TO ILEN, SEARCH FOR WATER COMPOSITION FAILED.
C
  500 CALL EXEC(11,ITIME)
      IT=ITIME(4)*100+ITIME(3)
      WRITE(LUN,104)IT
  104 FORMAT("CANNOT FIND BOTTOM COMPOSITOM OF WATER AT",I5)
C
C
  600 IBEG = IADD + 1
      IEND = IADD + ILEN
      WRITE(LUN,612) (ICOM(I) , I = IBEG,IEND)
      GO TO 200
C
C FORMAT STATEMENTS.
C
  205 FORMAT(' READING FROM GC HAS NOT CHANGE FOR',I5,/,
     *       ' COMPOSITION SET TO DEFAULT.')
  222 FORMAT(' GC OUTPUT IS NEGATIVE')
  310 FORMAT(' GC READING CHANGE GREATER THAN MAX ')
  612 FORMAT(40A2,/,40A2)
      END
```

```
FTN4
      PROGRAM GCSWT(3,80), GC AUTO. SAMPLING INITIATION PROGRAM  D
      CALL WAIT(5,2,IERR)
      CALL DOL(1,1,0,4,IERR)
      IF(IERR.NE.1) WRITE(1,100) IERR
      STOP
  100 FORMAT(' GCSWT CALL DOL ERROR, IERR = ',I2)
      END
```

```
FTN4
      PROGRAM BDC99(3,85), DISTILLATION COLUMN MONITOR PROGRAM  HK
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C          THIS PROGRAM MONITORS THE DISTILLATION COLUMN IN THE
C     ABSENCE OF AN OPERATOR. THE KEY VARIABLES ARE:
C
C       KEY VARRIABLES   ICHAN NO.  I.D.   HILIM   LOLIM    IDWN2
C       FEED FLOW LOOP        12     1     4900    1000      6MIN
C       DISTILLATE FLOW LOOP 10      2     4900    1000     30MIN
C       BOTTOM FLOW LOOP       8     3     5100    1000     30MIN
C       REFLUX FLOW LOOP     13      4     5000    1000     30MIN
C       STEAM FLOW LOOP        9     5     3800    1200     15MIN
C       COOLING WATER LOOP   11      6     5100    1200     15MIN
C       TOWER PRESSURE LOOP  16      7     4900    1200     15MIN
C       REBOILER LEVEL LOOP  17      8     4900    1100     15MIN
C       CONDENSER LEVEL LOOP 18      9     4900    1100     30MIN
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      COMMON ICOM(1)
      REAL DCDATA(11),CONA(11),CONB(11)
      INTEGER IPARAM(5),ITIME(5),IDATE(15),ITY1(11),ITY2(11),
     $ICHAN(11),IDATA(11),IDWN1(9),IDWN2(9),HILIM(9),LOLIM(9)
      DATA ICHAN/12,10,8,13,9,11,16,17,18,15,0/
      DATA CONA/2.5777,1.5205,1.5105,2.2975,2.25,71.278,
     $0.96988,1.0212,1.0723,0.12857,0.0010/
      DATA CONB/9*0.0,89.167,0.0/
      DATA NDATA,NTEST/11,9/,ITY1/10*1,2/,ITY2/8*1,3*2/
      DATA IDWN1/9*0/,IDWN2/5,3*30,4*15,30/,IDOWN/0/
      DATA HILIM/2*4900,5100,3800,5000,5100,3*4900/
      DATA LOLIM/4*1000,3*1200,2*1100/
C
C     FORMAT STATEMENTS
C
 2000 FORMAT(/,5X,"BDC99 UP @ ",15A2)
 2010 FORMAT(/,1X,"TIME",2X,"C.L. ERR",1X," 1 - FE ",1X," 2 - TP "
     $" 3 - BP ",1X," 4 - RE ",1X," 5 - ST ",1X," 6 - CW ",1X,
     $" 7 - PR ",1X," 8 - RL ",1X," 9 - CL "1X,"10 - XD ",1X,
     $"11 - XB ")
 2020 FORMAT(1X,2I2,12(1X,F8.3))
 2030 FORMAT(///)
C
C     INITIALIZATION
C
      CALL RMPAR(IPARAM)
      LUN=IPARAM(1)
      MULT=IPARAM(2)
      IRES=3
      ICHAN(11)=ICOM(8)+1
      DO 5000 I=1,9
      IDWN2(I)=IDWN2(I)/MULT
```

```
5000  CONTINUE
      CALL FTIME(IDATE)
      WRITE(1,2000) IDATE
      WRITE(LUN,2000) IDATE
      WRITE(LUN,2010)
      ISKIP=0
C
C     DATA ACQUISITION
C
5010  CALL ACQUI(LUN,NDATA,ITY1,ITY2,ICHAN,IDATA,DCDATA,CONA,CONB,
     $IERR)
      IF (IERR.NE.1) GO TO 5005
      CALL EXEC(11,ITIME)
      ERR=100.0*(DCDATA(1)-DCDATA(2)-DCDATA(3))/DCDATA(1)
      WRITE(LUN,2020) ITIME(4),ITIME(3),ERR,(DCDATA(I), I=1,NDATA)
C
C     VARIABLE LIMIT CHECKING
C
      CALL LMTCK(LUN,NTEST,IDATA,HILIM,LOLIM,IDWN1,IDWN2,IDOWN,
     $ISKIP)
      IF(IDOWN.NE.0) GO TO 5005
C
C     SUSPEND THE PROGRAM FOR MULT-MIN.
C
      CALL WAIT(MULT,IRES,IERR)
      IF (IERR.NE.1) GO TO 5005
      ISKIP=ISKIP+1
      IF (ISKIP.NE.45) GO TO 5010
      ISKIP=0
      WRITE(LUN,2030)
      WRITE(LUN,2010)
      GO TO 5010
C
C     DISTILLATION COLUMN SHUT DOWN
C
5005  CONTINUE
      CALL DOL(1,1,8,8,IERR)
C
C     RESET THE ECO 15 SEC. AFTER THE SHUT DOWN
C
      CALL WAIT(15,2,IERR)
      CALL DOL(1,1,0,8,IERR)
      STOP
      END
C
C
      SUBROUTINE LMTCK(LUN,NDATA,IDATA,HILIM,LOLIM,IDWN1,IDWN2,IDO
     $ISKIP)
      INTEGER IDATA(1),HILIM(1),LOLIM(1),IDWN1(1),IDWN2(1),ITIME(5
     $IDATE(15),LABEL(9)
      DATA LABEL/2HFE,2HTP,2HBP,2HRE,2HST,2HCW,2HPR,2HRL,2HCL/
```

```
2000  FORMAT(/,5X,"A L E R T     LOOP - ",A2)
2010  FORMAT(/,5X,"D A N G E R     DIST. COL. DOWN @ ",15A2,/,5X,
     $"DOWN LOOP =",A2)
2020  FORMAT(/,5X,"BDC99 DOWN @ ",15A2,5X,"D.L. = ",A2)
      CALL FTIME(IDATE)
      DO 5000 I=1,NDATA
      IF(IDATA(I).LE.LOLIM(I).OR.
     $IDATA(I).GE.HILIM(I)) GO TO 5010
      GO TO 5020
5010  IF(IDWN1(I).GT.IDWN2(I)) GO TO 5030
      IDWN1(I)=IDWN1(I)+1
      IDOWN=0
      WRITE(LUN,2000) LABEL(I)
      ISKIP=ISKIP+3
      GO TO 5000
5020  IDWN1(I)=0
      IDOWN=0
5000  CONTINUE
      RETURN
5030  IDOWN=1
      WRITE(LUN,2010) IDATE,LABEL(I)
      WRITE(1,2020) IDATE,LABEL(I)
      RETURN
      END
C
C
      SUBROUTINE ACQUI(LUN,NDATA,ITY1,ITY2,ICHAN,IDATA,DCDATA,
     $CONA,CONB,IERR)
      COMMON ICOM(1)
      DIMENSION DCDATA(1),CONA(1),CONB(1)
      INTEGER ICHAN(1),IDATA(1),ITY1(1),ITY2(1)
2000  FORMAT(/,5X,"DIST. COL.  -  LOOP ",I2,"     IERR = ",I2)
      DO 5000 I=1,NDATA
      IF (ITY1(I).EQ.2) GO TO 5010
      CALL AIRD(1,ICHAN(I),IDATA(I),IERR)
      IF (IERR.EQ.1) GO TO 5020
      WRITE(LUN,2000) I,IERR
      RETURN
5020  IF (IDATA(I).GE.1000.AND.IDATA(I).LE.5000) GO TO 5021
      IF (IDATA(I).LT.1000) IDATA(I)=1000
      IF (IDATA(I).GT.5000) IDATA(I)=5000
5021  RDATA=0.0250*FLOAT(IDATA(I))-25.0
      GO TO 5030
5010  IERR=1
      IDATA(I)=ICOM(ICHAN(I))
      RDATA=FLOAT(IDATA(I))
      GO TO 5030
5030  IF (ITY2(I).EQ.2) GO TO 5040
      DCDATA(I)=CONA(I)*SQRT(RDATA)+CONB(I)
      GO TO 5000
5040  DCDATA(I)=CONA(I)*RDATA+CONB(I)
5000  CONTINUE
      RETURN
      END
```